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CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

Guidelines for Trenchless Technology:

Cured-in-Place Pipe (CIPP), Fold-and-Formed Pipe (FFP), Mini-Horizontal Directional Drilling (Mini-HDD), and Microtunneling

by

Robert D. Bennett, Leslie K. Guice, Salam Khan, Kimberlie Staheli

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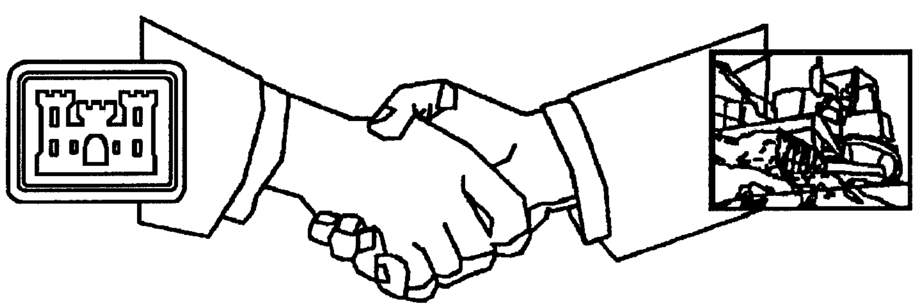

A Corps/Industry Partnership to Advance Construction Productivity and Reduce Costs

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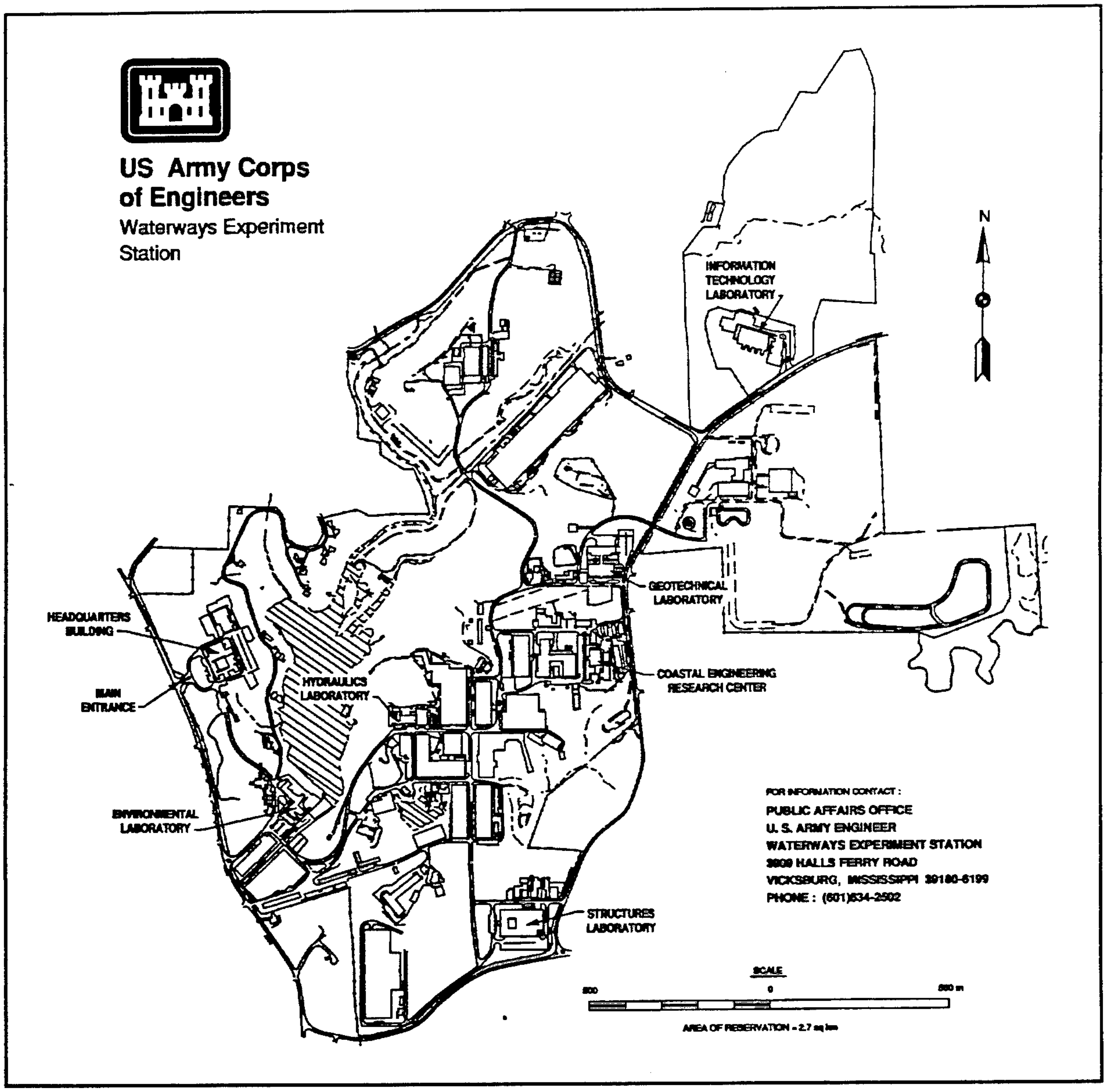

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Contents

List of Tables

List of Figures

Preface

The guidelines for trenchless technology described in this report were developed for Headquarters, U.S. Army Corps of Engineers (HQUSACE), by the U.S. Army Engineer Waterways Experiment Station (WES) in cooperation with the Trenchless Technology Center (TTC) at Louisiana Tech University. This research and development (R&D) was conducted under the Construction Productivity Advancement Research (CPAR) Program. The guidelines mark the completion of the 3-year CPAR project "Trenchless Construction: Evaluation of Methods and Materials to Install and Rehabilitate Underground Utilities." Messrs. A. Wu and F. Eubank were the HQUSACE Technical Monitors. Mr. David Mathis was the HQUSACE CPAR Program Manager.

These guidelines were developed by a project team from WES and Louisiana Tech University. The Principal Investigator for WES was Mr. Robert D. Bennett, Soil and Rock Mechanics Division (S&RMD), Geotechnical Laboratory (GL), and the co-Principal Investigators for the industry partner were Dr. Tom Iseley, former Director of TTC, and Dr. Leslie K. Guice, Head of the Civil Engineering Department at Louisiana Tech University. Dr. Iseley organized the industry partner's research team and led them through completion of all field and laboratory testing. He is presently Chairman of the Department of Construction Technology at Indiana University/Purdue University. Dr. Iseley provided the vision, enthusiasm, and sense of urgency that was contagious to all team members. Dr. Iseley co-authored research reports and papers on several aspects of the R&D. Dr. Guice guided all aspects of the research on rehabilitation systems and supervised the planning, design, and construction of the large-scale test facility built at Louisiana Tech University for the long-term liner product tests. He developed the test procedures and supervised the test program, data acquisition, and evaluation. Dr. Guice was the principal author on all project research reports in this area, including the rehabilitation guidelines in this report.

Other industry partner team members and their contributions were:

> Mr. Christopher R. Norris, Roy F. Weston, Inc., who had primary responsibility for execution of the long-term test program on rehabilitation products. Mr. Norris was involved in the planning, design, and construction of this test facility and the testing. He collected the test data, assisted in the analysis, and was a co-author on the research report for this task. He had the lead role in the state-of-the-art review of microtunneling, and assisted in the field tests of the microtunneling and mini-horizontal directional drilling (mini-HDD) systems at the WES test facility.
>
> Mr. Ron Thompson, vice-president of Roy F. Weston, Inc., who provided advice in planning the project and reviewing reports.

Mr. Salam Khan, Louisiana Tech University, who assisted in the field evaluation of mini-HDD systems, the state-of-the-art review of mini-HDD, and the development of the mini-HDD guidelines. He was also a contributing author for all reports in this area of research.

Dr. Mohammed Najafi, formerly with Louisiana Tech University, who had major roles in project management for the industry partner and in the state-of-the-art review of rehabilitation systems. He contributed to all aspects of the project, authored the rehabilitation state-of-the-art report, and co-authored several research papers on various aspects of the project.

Dr. Tom Straughan, Louisiana Tech University, who made significant contributions to the planning, execution, and analysis of the long-term tests on rehabilitation systems. He co-authored the corresponding research report on this element of the research.

Dr. Steven McCrary, Louisiana Tech University, who made significant contributions to the state-of-the-art review of mini-HDD systems and co-authored the resulting research report.

Mr. Larry Slavin, Bellcore, who provided constructive suggestions and thorough review for the mini-HDD field evaluation, mini-HDD state-of-the-art review, and guidelines development.

Mr. Nitham Khanfar, former student at Louisiana Tech University, who provided significant contributions during the microtunneling field tests and the collection and analysis of test data.

Mr. Yueming "Jimmy" Li, former student at Louisiana Tech University, who played a key role in the analysis of the enormous amount of data from the long-term tests of rehabilitation systems.

Dr. Raja Nassar, Louisiana Tech University, who provided significant support in the analysis and interpretation of the rehabilitation tests.

Mr. Dennis Tatum, Louisiana Tech University, who provided crucial assistance in the design, construction of the rehabilitation test facility, and execution of the rehabilitation tests.

Mr. Michael Beard, former student at Louisiana Tech University, who played a key role in the microtunneling tests and data acquisition from the tests.

Messrs. Shannon Conner, Paul Tennis, Jason Bailey, Hong Lin, Norman Nassif, and Alan Atta-Allah who contributed to several elements of the project, particularly the rehabilitation guidelines.

Dr. Paul Hadala, interim Director of the TTC, who joined the industry partner team in 1994 and provided the organizational skills, leadership, and enthusiasm needed to boost the completion of all remaining project milestones, including these guidelines. He provided extensive technical review and advice on the mini-HDD and rehabilitation sections in this capacity. Dr. Hadala formerly was the Assistant Director of GL, WES, and in this

capacity, provided valuable and timely advice to the WES Principal Investigator on all aspects of the R&D.

Mrs. Daphne Harrington, TTC, who provided administrative and typing support, helped organize meetings and conferences, and made the tasks of all team members a lot easier.

WES team members and their contributions include:

Mr. Perry A. Taylor, S&RMD, who played a critical role in the planning, design, and construction of the WES microtunneling test facility. He was responsible for field operations and logistics during the extensive microtunneling tests and assisted in the evaluation of test data and preparation of reports.

Ms. Kris McNamara, S&RMD, who provided crucial assistance during the microtunneling tests, including data acquisition and preparation of tables, figures, and other graphics for technical reports and papers.

Ms. Kimberlie Staheli, who brought a wealth of insight and valuable personal experience in microtunneling when she joined the WES research team in 1995. Her background in contracting added balance and provided much needed focus in sorting through the substantial body of information developed during the project. She energized the completion and made substantial contributions as a co-author of the microtunneling guidelines.

Mrs. Teresa Shirley, S&RMD, who provided typing support in preparation of the guidelines report, technical papers, and correspondence.

Mrs. Mary Anne Kirklin, S&RMD, who provided typing support and assisted in preparation of graphics for numerous presentations and papers.

Valuable assistance was provided throughout this project by a number of secondary industry participants. This assistance ranged from providing equipment, materials, and manpower for field and laboratory tests to technical review of project results and reports, including these guidelines. This project was successful because these individuals and organizations contributed unselfishly so that the entire trenchless industry would benefit. The list below probably does not include all, and sincere apologies are offered to any who may have been inadvertently omitted. The list below is grouped into three major research areas, although some organizations and individuals provided assistance in all areas of the work.

Rehabilitation:

Mr. Lynn Osborne and Mrs. Lisa Harris, Insituform Technologies, Inc.
Dr. John Gumbel, Insituform, Ltd.
Mr. Jay Schrock, JSC, International Engineering
Mr. Richard Thomasson, Washington Suburban Sanitary Commission
Mr. George McAlpine, Danby of North America, Inc.
Mr. Doug Kleweno and Mr. Seth Hinley, Inliner USA, Inc.
Mr. Michael Glasgow, Phillips Driscopipe, Inc.
Mr. Michael Spencer, CommCorp

Mr. Scott Mortimer and Mr. Mark Wallborn, KA-TE USA, Inc.
Mr. Allen Thomas, *Trenchless Technology Magazine* and Executive Director, NASSCO
Mr. C. J. Follini, Earthline Corp., Superliners USA, Inc.
Mr. Jose Collazo, Spiniello Ltd., Inc.
Mr. Al Colthorp, Insituform Mid-America
Mr. Anthony Almeida, City of Dallas
Mr. Joe Barsoom, City and County of Denver, Wastewater Management Division
Mr. Michael Bank, Lamson Vylon Pipe
Mr. Him Lo, Shell Development Corp.
Mr. Dee Rice and Mr. Dick Nieman, Pipeliners, Inc.
Mr. Ivan Mandich, Delta Engineering

Mini-HDD:

Mr. Mark Kern, Dr. Gerald Stangl, and Mr. Scott Pollman, Charles Machine Works
Mr. Dave Huff, Midwest Microtunnel Inc./TT Technologies, Inc.
Mr. Steve Schultz, Bor-Mor, Inc.
Mr. Chris Brahler, TT Technologies, Inc.
Mr. Bernie Krzys, *Trenchless Technology Magazine*
Mr. Skip Paxton, Petroflex North America (PNA)
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Messrs. Phil Coller, David Abbot, James Tan, and Ray Post, Iseki, Inc.
Mr. Ronnie Bledsoe, American Microtunneling/Volusia Construction
Messrs. Bill Frost and Troy Stokes, American Microtunneling
Messrs. Rick Turkopp, Tim Naccarato, and Ed Kocurek, Hobas Pipe USA, Inc.
Mr. Bill Gilman, McLaughlin Microtunneling, Inc.
Mr. Frank Canon, Baroid Drilling Fluids, Inc.
Mr. Michael Argent, Permalok Corp.
Dr. Tom Garrett, Messrs. Robert Lys, Howard Preslar, and Billy Nelson, Mission Clay Products
Dr. Edward J. Cording, University of Illinois
Mr. Steve Kramer, Jason Consultants
Messrs. Mike Ellis and Ernie Thornton, Western Utility Contractors
Mr. Bill Crowder, Crowder Construction
Mr. Jim Bartley, Jim Bartley and Associates
Ms. Freida Brinskelle, American Concrete Pipe Association
Mr. Dan Dobbels, Haley & Aldrich, Inc.

The staff and technical committee members of North American Society of Trenchless Technology (NASTT) are especially thanked for their reviews, advice, and support throughout this project, particularly Mrs. Janet Popp, Executive Director; Miss Sue Caffrey; and Mr. Ed Kawala.

The Laboratory partner's research was conducted under the general guidance of Dr. Don Banks, Chief, S&RMD, and Dr. William F. Marcuson III, Director, GL. Mr. William F. McCleese was the WES CPAR point of contact.

At the time of the publication of this report Dr. Robert W. Whalin was Director of WES. COL Bruce K. Howard, EN, was Commander.

Executive Summary

These guidelines mark the completion of the Construction Productivity Advancement Research (CPAR) project "Trenchless Construction: Evaluation of Methods and Materials to Install and Rehabilitate Underground Utilities." CPAR is a cost-shared Corps of Engineers and construction industry research program. CPAR was created to help the U.S. construction industry improve productivity and regain its competitive edge by building on the foundation of the existing Corps research and development (R&D) programs and laboratory resources through the leveraging effect that cost-shared partnerships provide. The overall objective of the CPAR program is to facilitate construction productivity improvements through cooperative R&D, field demonstrations, technology transfer, and commercialization. The Corps, as one of the largest users of construction services and products, will benefit from productivity increases achieved through this program. Approximately 60 projects have been funded under the CPAR program from its inception in 1989 through 1994 with the Corps providing over $25 million and the construction industry providing over $38 million in matching funds.

The overall objective of this 3-year project conducted by the U.S. Army Engineer Waterways Experiment Station (WES) and the Trenchless Technology Center (TTC) at Louisiana Tech University was to develop guidelines that owners, engineers, and contractors could use to evaluate and select appropriate trenchless methods and equipment for their project requirements and site conditions.

The guidelines focus on the three major elements of trenchless technology investigated in this study: rehabilitation of existing pipelines using cured-in-place (CIPP) and fold-and-formed pipe (FFP) methods, installation of small-diameter (2- to 10-in.) pipelines using mini-horizontal directional drilling (mini-HDD), and installation of larger diameter pipelines using microtunneling. The guidelines are based primarily on the results of extensive laboratory and field investigations, the scope and potential impact of which exceeds any previous efforts. The guidelines are also based on state-of-the-art reviews, interviews with industry experts, and studies of case histories. The guidelines are presented in a format patterned after Corps of Engineers Guide Specifications, but with more detailed information. The intent is to make it relatively easy to develop project specifications, using the information and references provided, by tailoring this to particular project requirements and site conditions.

The greatest opportunities to add value and reduce cost of a project occur in the early planning and feasibility phases. Adoption of well-reasoned modifications and value engineering proposals can have beneficial impacts during almost any stage of a project, but the greatest impact is at the

beginning. If these guidelines help the reader understand the applications, limitations, and issues that must be addressed for trenchless technology, project objectives will have been met and some value added in the challenging task of renewing America's aging infrastructure.

Rehabilitation

Pipeline rehabilitation has been revolutionized through the use of CIPP and FFP liner processes. CIPP is a liquid thermosetting resin-saturated material that is inserted into the existing pipeline by hydrostatic inversion or air inversion or by mechanically pulling with a winch and cable. The FFP process utilizes a thermoplastic pipe which is folded or deformed to reduce the cross-sectional area, then pulled into place, expanded, and rounded using heat or pressure to conform to the internal shape and size of the existing pipe. The CIPP and FFP techniques are beginning to be widely accepted across the United States as more and more utility system owners have experimented with the products with satisfactory results. With an expanding market, more competitors are entering the field, which should make pricing become more competitive and should increase the percentage of jobs which are rehabilitated with these nondisruptive techniques.

CIPP and FFP products are actually engineered systems with few of the characteristics of "off-the-shelf" products. For FFP products, there are standard dimension ratios (liner diameter-to-thickness ratio), but the methods of installation and materials will vary by manufacturer. Standard resin systems are typically used in CIPP products, but there can be significant variations in the properties of the final product. CIPP systems vary in tube construction, finished liner dimensions, installation methods, and curing methods. To get a quality product through fair and competitive bidding, the utility owner must properly design and specify the system. With the rapid emergence of these rehabilitation processes, there has been little independent information to assist the engineer in evaluating, designing, and specifying the best product for the given conditions. From these guidelines, the engineer will obtain an understanding of what should be considered, what data are available to validate design equations, and other resources for assisting in the design and specification of rehabilitation systems.

The capabilities of CIPP and FFP systems are growing and becoming better understood as more research, development, and field evaluations are completed. CIPP products currently range from 4 to 108 in.[1] in diameter with a maximum installation length of 1,000 to 3,000 ft. FFP products range from 4 to 18 in. in diameter with a maximum installation length of 500 to 700 ft. Elbows, bends, and flat sections in pipe lines can be successfully lined, but they require special design considerations. Flow bypassing must be feasible for sewers that are to be relined.

Unsaturated polyester resins are most commonly used for CIPP systems carrying domestic sewage. Vinyl ester and epoxy resin systems can be used where special resistance to corrosion, solvents, and high temperatures are needed. Polyvinyl chloride (PVC) and high-density polyethylene (HDPE), the two materials used for FFP, have proven effective in resistance to corrosion and abrasion after many years of use in other sewer system applications.

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[1] A table of factors for converting non-SI units of measurement to SI units is given on page 10.

Some standard test methods, practices and material specifications related to CIPP and FFP systems have been developed by the American Society for Testing and Materials (ASTM). It is essential that a thorough evaluation of the sewer system including assessments of the infiltration and inflow (I/I), the structural condition, and the hydraulic condition be conducted prior to the design and selection of a rehabilitation process. Some rehabilitation techniques are more effective in dealing with certain types of failure conditions than others; thus rehabilitation that addresses failure symptoms without considering failure mechanisms invites costly errors. The applicability of repair methods should be assessed in relation to special construction problems, sizes, and shapes of existing pipes, pipe conditions to be corrected, and desired capacities of the rehabilitated system. Assessing the condition of a sewer should typically include a review of system records, a physical survey, physical testing, preparatory cleaning, internal inspection, and an analysis of flow, corrosion, and structural conditions. If proper considerations are given, CIPP and FFP systems can be effectively used to minimize I/I, to improve the structural condition and prevent failure under loading, and to enhance the hydraulic capacity of a sewer. However, the engineer must have a good understanding of the existing sewer conditions so that an effective design can be prepared.

For evaluating corrosion resistance, suppliers have tested their resins in standard chemicals. In special conditions where there is exposure to unusual chemicals that are not encountered in standard domestic sewage, special testing may be required. Chemical corrosion may be accelerated by stress in the liner as a result of deformations which occur after the liner hardens, particularly when fiberglass-felt composite tubes are used. While some standards for testing of chemical resistance exist, the engineer must use judgment to establish when additional testing is required and what the pass-fail criteria for nonstandard tests should be. In the structural design of liners, the degree of degradation of the original pipe governs the load the liner must support. The two types of structural design conditions typically considered are partially deteriorated and fully deteriorated. In a partially deteriorated condition, the pipe is considered to be structurally sound at the time of rehabilitation and is expected to remain sound throughout the design life of the rehabilitated pipe. The original soil-supported pipe will continue to support soil loads and live loads. The installed pipe liner will be expected to maintain the external hydrostatic pressure resulting from water that permeates through cracks in the deteriorated host pipe.

The traditional buckling formula for liners subjected to hydrostatic pressure is based on the classical Timoshenko buckling formula for unconstrained circular tubes. This approach has been modified by factors that account for the restraint provided by the host pipe and ovality. This equation conservatively predicts CIPP and FFP buckling with ovality of the host pipe of up to 10 percent. Where the host pipe is more than 10 percent out-of-round, special design considerations are required. In a fully deteriorated condition, the existing pipe is not considered to be capable of supporting the soil and live loads, or may be expected to reach this state during the design life of the rehabilitated pipe. In this case, the installed liner is assumed to support all loads through interaction with the surrounding soil. The standard flexible pipe design approach which accounts for the buckling resistance, bending stresses due to ovalization, pipe stiffness, and deflections is typically used. Because adequate lateral support from the soil is essential for the flexible pipe design, it may be advisable to conduct soil investigations of the soil adjacent to the pipe for sizeable, large-diameter projects. To assume that all sewers are fully deteriorated may result in an overly conservative design and reduce the competitiveness of CIPP and FFP liners compared to more traditional methods. Most utility system owners specify a sewer design life of 50 years. When a plastic is subjected to load over a long period of time, the material creeps and the pipe exhibits a reduction in buckling resistance. Tests to evaluate the long-term behavior of

CIPP and FFP products were conducted as part of this CPAR project; and a method to evaluate the strength and stability of plastic pipe under long-term loads has been established.

The current practice for the analysis of a liner is shown to estimate long-term buckling pressures which are generally less than the extrapolated experimental data. If the engineer assumes appropriate values of the modulus of elasticity, creep reduction factor, and restraint factor, the current practice is conservative for the products evaluated under conditions imposed in this test program. However, these factors cannot be determined independently of each other, but should be based on reliable test results which consider the total system behavior. Short-term material tests alone do not accurately reflect the long-term behavior of CIPP and FFP products.

Field installations of the products are typically not under ideal conditions, and designers must impose factors of safety which account for uncertainties that exist in the field. Currently, factors of safety for the buckling resistance of liners range between 1.5 and 2.5, depending on the confidence the designer has on the conditions imposed. As the understanding of material behavior is increased, the safety factors can possibly be reduced, resulting in less conservative and more cost-effective designs. Safety factors are also highly dependent upon the quality of the product and installation, which are directly affected by the attention to design details and construction workmanship.

In considering the impact CIPP and FFP linings have on the hydraulic capacity of the pipe, the system-wide implication of the project should also be evaluated. Rehabilitation can impact the hydraulic performance by increasing or decreasing the flow through the pipe. The change in pipe size typically reduces the flow cross-sectional area and hydraulic radius components of pipe flow calculations. Although these reductions in flow exist, pipe capacity can often be maintained due to the reduction in infiltration and inflow entering the system and reduction in the roughness of the host pipe. Improvements in one area of the sewer system may result in more frequent surcharge in structurally degraded pipes, causing additional failures and problems in other areas.

The design of a liner system may prove to be inadequate to the owner if proper consideration is not given to the details at service of lateral and manhole tie-ins. The contractor must locate lateral tie-ins within a lined section before and after installing the liner. Remote-control cutting methods and closed-circuit television can be used to open the rehabilitated pipe to service laterals, and robotic technologies can be used to prepare and repair surfaces of the host pipe. If designed to reduce inflow and infiltration, the liner should be adequately sealed at laterals to ensure that there is no inflow into the pipe.

The material components of CIPP must be carefully specified. The tube must be compatible with the specified resin system so that debonding, delamination or other forms of degradation do not occur due to incompatibility of materials. Allowances must also be made for the stretching of the tube circumferentially and longitudinally. Proper saturation of the resin to fill all voids in the tube and accounting for resin migration is essential. For proper curing, close control on the heat source, rate of heating, distribution of temperatures, and heating durations are required. Some of the factors that could lead to improper curing of the resin include ruptures in the tube, equipment malfunctions, or lack of attention given to temperature-monitoring instruments.

The collection of field samples for evaluating the installed properties of the liner is important. Field installation and curing conditions can lead to properties of the installed liner which are

significantly different from design or laboratory conditions. Samples may also be used for verification of the installed thickness and other properties. Construction-related issues are also important in selecting a particular rehabilitation technique. The main construction issues to be considered include safety, preparation, methods of working, and onsite supervision. Most importantly, the engineer and contractor should be familiar with the installation process to be performed; and the installation crew must be well-trained and experienced in the techniques employed.

Keeping the public notified of the activities associated with rehabilitation of their sewers is often a critical measure of the success of the project. Affected parties must be informed when their service laterals will be out of commission, of odors resulting from the curing of resins, of noises associated with installation equipment, and of potential traffic disruptions.

Mini-HDD

Mini-HDD methods are used typically for the installation of small-diameter lines (2- to 10-in.), up to 600 ft in length, and up to 15 ft deep. Some systems can be used for installations as deep as 30 ft. The feasibility of the mini-HDD technique depends on the ground conditions, the accuracy required, and that achievable for both alignment and grade. Mini-HDD is not currently practical for gravity sewer lines with precise line and grade tolerances.

The mini-HDD process involves the creation of a small-diameter (2 to 4 in.) pilot bore hole using steerable mechanical fluid-jet cutting tools, followed by pullback of the utility line through the borehole. The borehole is often enlarged with the help of a reaming assembly to accommodate the utility line. Although a few dry systems exist, most mini-HDD systems use a slurry to stabilize the walls of the borehole and to reduce the frictional drag on the cable line or pipeline being installed. Most mini-HDD systems manufactured in the United States use fluid-assisted mechanical cutting technology. Survey systems locate the drill head position so that steering corrections can be made as the boring progresses. Steering corrections are made in soils by rotating the slanted cutter shoe to the desired orientation and then advancing the string without rotating. In weak rock or very stiff soils, a bent sub may be used in conjunction with a downhole mud motor to make steering corrections.

In the pullback operation, the pipe is attached behind the reaming assembly, and a gripper that holds the product pipe is connected to the swivel while the pipeline is pulled into the borehole. Among the most common product line or pipe materials used are HDPE, PVC, steel (for small-diameter pipes), copper (for service lines), and cables. Potentially vulnerable (e.g., fiber-optic) cables should not be pulled directly, but may be contained inside the product pipe (e.g., HDPE pipe) during the pulling operations or may be carefully placed after installing the host pipe. The product pipe or utility line should be installed in one continuous operation, preferably without pause, and should protrude a sufficient distance beyond the exit and entry points to allow proper termination or connection at a later time, as required.

The primary selection criteria for a mini-HDD machine are thrust/pullback and torque capabilities. However, project-related requirements such as length of installation and diameter of the product pipe play an important role in the selection process. Typically, mini-HDD machines

have thrust/pullback and torque capabilities of less than or equal to 20,000 lb and 950 ft-lb, respectively.

For mini-HDD installations, the magnitude of the drilling fluid pressure should not be a major concern with regard to erosion and formation of voids because of the relatively low fluid volumes pumped. For most soils, operating pressures from 300 to 1,400 psi at the drill head are sufficient to maintain proper fluid flow. For harder soil formations, the higher range of operating pressures (1,200 to 1,400 psi) are more suitable. For unstable soils, e.g., unconsolidated sand, low operating pressures of 300 to 500 psi often would be suitable to control seepage and hole cutting.

Different designs of drill heads include compaction heads, cutting heads, and various combinations. Different types of reamers are available including cutting, tri-action, compaction (or packer), barrel, blade reamers, or combinations. The size of mini-HDD reamers varies from approximately 4 to 12 in. in diameter. In general, the compacted hole diameter should be at least 1.5 times the product pipe diameter.

The mini-HDD method is typically capable of turning a minimum radius of 125 ft with a 1-1/2-in.-diameter drill pipe. The mini-HDD method is best suited for clay-type soils. The method is also quite successfully used in sandy soils by adding bentonite in the drilling fluid to ensure borehole stability. Hard soils, rocks, and gravelly soils present difficult challenges to penetration and steering control; therefore, use of the mini-HDD method in these ground conditions may be inappropriate.

The objectives of site investigations for mini-HDD projects are to assess the feasibility of completing the installations, to minimize the likelihood of damaging existing facilities in the area, and to provide the information needed to allow selection of the most appropriate construction technique and equipment consistent with the site conditions. The extent of site investigations depends on the location and complexity of the project and the risk associated with the project. In addition to soil investigation, the types, number, and locations of existing utility lines in the project area should be identified. The subsurface investigation usually consists of reviewing available geological and geotechnical information to determine soil type, strength, groundwater depth, and permeability of underlying soil. The potential for occurrence of contaminants in the soil, natural or man-made obstacles such as boulders, large construction debris, etc., should be determined. Subsurface conditions that are not revealed in the contract documents will generally be treated as changed conditions, and any extra costs involved may be claimed for payment as extra work by the contractor.

For large, high-risk, or environmentally sensitive projects, detailed subsurface investigations are recommended. Suggested parameters to be evaluated would include soil type, unconfined compressive strength, unit weight, particle size, moisture content, plasticity characteristics, groundwater depth, and permeability of the underlying soil. For projects in rock, unconfined compressive strengths, abrasiveness, and rock quality designation (RQD) are needed. A limited number of strategically located borings can be used to complement available information.

The typical profile of a mini-HDD bore includes an inclined and vertically curved section at the transition near entry end (also possibly at exit end) and the main "straight" horizontal section for the intermediate length. The depth of cover should typically be a minimum of 3 ft or the depth

specified by the owner in the horizontal section of the bore route. The minimum depth of cover requirement will help minimize the possibility of drilling fluid leakage to the surface and surface deformation in the form of heave/settlement. In designing the bore route, there should be a designated clearance between the existing utility lines and the new utility line. Buried underground hazards (including electrical cables; natural gas lines; water lines; pipes carrying other chemicals, liquids, or gases; storage tanks; and telecommunications and CATV cables) must be identified, located, and avoided.

The owner must establish the requirements for accuracy of mini-HDD bores. The requirements should be set in terms of allowable horizontal and vertical deviations (tolerances) at entry and exit points and at stated intervals or locations between these points. The tolerances specified must be based on what is required for satisfactory performance and must be balanced against what is reasonably achievable. Mini-HDD system manufacturers generally state the accuracy achievable with their locator system is ± 2 to 5 percent of depth, up to a maximum depth of 30 ft. Some manufacturers claim that installations can be as deep as 50 ft without hardwired transmitters and 75 ft or greater with hardwired transmitters. However, optimum accuracy also depends on use of equipment that is in good working condition, an operator who is qualified and experienced, and operating conditions that are optimal. Other factors that influence achievable accuracy include the length, depth, layout of the bore, topography of the terrain, subsurface conditions, utilities and obstructions, intervals between measurements, and operator skill. An excavation is required to verify actual location, and a survey measurement is needed to establish deviation both horizontally and vertically. Under normal circumstances, mini-HDD systems should be capable of achieving installation accuracies of ± 12 in. vertically and horizontally. When close tolerances are set by the engineer, locator readings and steering corrections must be made more frequently, which slows progress and increases costs; however, these may be reasonable trade-offs. In cases where nearby utilities necessitate use of close tolerances, these tolerances should be required at all points between entry and exit. The requirements for frequency of locator measurements as well as remedial actions when measurements exceed tolerances should be stated. For example, requirements may be established for making gradual steering corrections to avoid sharp bends that may adversely impact both the drill rod and product pipe.

Drilling fluid is used to improve the drilling performance in a mini-HDD process. Specifically, drilling fluids stabilize the borehole, reduce the torque on the drill pipe and pull-in force on the product pipe, cool the drill bit and transmitter sonde, and remove cuttings. Trade-offs are often required to satisfy all these drilling fluid functions with regard to type of drilling fluid, volume, and pressure.

The drill unit should be positioned at an appropriate setback distance such that the required depth, starting from the entry point, can be achieved. Typically, the entry angle for a mini-HDD bore should be in the range of 5 to 20 deg, depending on topographical conditions and depth requirements.

The most widely used locating technique for mini-HDD is the walk-over surface locator system. In this system, a downhole transmitter or sonde (contained inside the drill head housing) transmits a signal to an electronic receiver unit carried by the locator operator to determine the location and depth of the downhole drill head. The receiver determines pitch, roll, temperature, and battery charge level. On projects where tolerances are small, locator readings at 5-ft intervals are generally recommended. If the bore route is complicated and passes in the vicinity of other utility

lines, more closely spaced locating points may be necessary. For straight, simple bores, locator readings may be taken at 10-ft or greater intervals, depending on the required accuracy and crew skill.

The new product pipe or utility lines may require postinstallation pressure testing for possible damage that may have occurred during the pullback operation, depending on the ultimate use of the pipe. When the installation is complete, plan and profile information on the installed product pipe should be provided showing permanent references and other adjacent surface and subsurface features. The depth and position of the pipe should be included for preparation of the as-built drawings. In addition, "pot-holes" might be excavated at critical locations to verify the depth and position of the installed pipe. Regarding the as-built records, it may be desirable to record drilling fluid usage (gallons per foot of bore). Such information may be useful in estimating the volume of drilling fluid to be used in future projects and may relate to site clean-up issues. Similarly, thrust, torque, and time required to complete the drilling or pullback operation should be recorded. This information is useful for determining the locations and potential causes of unusual occurrences or problems or for use in future projects. Any migration or spilling of drilling fluid at the surface or into adjacent streets and storm drains must be promptly contained and cleaned. All excavations must be backfilled and properly compacted. For water or gas lines, no backfill should be placed in pits, trenches, or other excavations until the line has been inspected and passed hydrostatic and leakage tests. After completing the job, the surface area should be restored to its original condition.

In addition to the obvious requirements regarding scope of work, plans, and specifications, minimum performance requirements and performance period, and measurements and payments, additional submittals from the owner of the utility lines to potential bidders are needed. These should include prequalifications of contractors, site investigation reports, requirement for protecting existing structures and site features, inspection and notification requirements, remedial action requirements, and safety concerns.

Prequalification of contractors allowed to bid mini-HDD projects is a sensitive issue. Reasonable arguments against prequalification include the impact on competition and costs and the potential for misuse. For small, relatively simple projects, prequalification is unnecessary. However, on complex or large projects in which emerging technologies may be appropriate, prequalification of bidders has been used to attempt to increase the probability of successful completion of projects and should be considered as a useful tool. On projects where prequalification is considered necessary, the prequalification requirements should be carefully developed and enforced to ensure fairness to bidders and the owner.

Most contract documents cannot or do not cover all the problems that may occur on a project. The owner and engineer should strive to identify anticipated problems and should establish or request submittals of a course of action for the contractor to follow in the event that problems are encountered.

Microtunneling

Microtunneling is a remotely controlled, guided, pipe-jacking process that provides continuous support to the excavation face and does not require personnel entry into the tunnel. Applications are typically for gravity sewers, although other specialized projects have been constructed using this method. Microtunneling methods may be appropriate where pipeline depths are greater than 15 ft, where areas are sensitive or congested, where marginally or unstable ground conditions exist, where construction takes place below the water table, or where extensive contamination zones exist. A successful microtunneling project requires proper site investigations, appropriate consideration of design criteria, preparation of comprehensive bid documents, accurate contractor submittal information, careful execution by a highly skilled operator and crew, and a knowledgable, experienced contractor.

The site investigation requirements for microtunneling are no different in principle than for other subsurface excavation and tunneling projects. The subsurface information required can be obtained, interpreted, and applied to microtunneling using existing technology. Claims are often made that microtunneling can be used under a variety of ground conditions from soft soils to rock, including mixed face and boulder ground, above or below the water table. Microtunneling methods can be used under a wide range of conditions, and machines can be selected, set up, and operated by highly skilled crews to provide satisfactory results under these conditions. However, a given combination of machine, configuration, and operating practice cannot, in general, be expected to perform at top efficiency under all possible ground conditions. The potential range of ground conditions that can adversely impact the performance of the machine must be identified and the range of potential adverse effects that the machine may have on the site and surrounding ground features must be determined.

In the case of microtunneling, most projects are relatively small, which tends to limit the extent of the geotechnical investigation. Therefore, maximum effective use must be made of existing information supplemented with new borings and other investigative techniques. New boreholes provide the basis for confirmation of inferences and preliminary conclusions drawn from study of regional and site geology, geophysical surveys, and analysis of logs of nearby borings and wells from previous projects. Boreholes provide a wealth of information, including the undisturbed samples required for reliable characterization of important site features. Boreholes must be strategically placed to get the most valuable information at the most critical locations. In general, boreholes should be located at all shaft locations and at intermediate points not greater than 300 ft apart. Boreholes provide the most reliable indication of conditions to be encountered if they are located along the proposed centerline of the tunnel. However, if boreholes are located along the centerline, they must be properly abandoned, by tremie grouting with a bentonite-cement grout mixture, to eliminate the potential for loss of slurry through the borehole as the tunnel passes that location.

Site characteristics that exert the greatest influence on microtunneling projects include groundwater, obstructions, rock, difficult ground conditions (such as raveling, running, flowing, squeezing, or swelling ground, or mixed-face conditions), contaminated groundwater or soil, existing utilities, building foundations, and environmentally sensitive features. Depth to groundwater should be confirmed by borings at all shaft locations and at intermediate points not greater than 300 ft apart. Obstructions are defined as objects that lie completely or partially within

the cross-sectional areas of the planned pipeline excavation and that prevent continued forward progress of the microtunneling machine. In general, when obstructions are encountered, the face must be exposed to allow removal. It is therefore imperative to develop plans for dealing with obstructions, physically and contractually, before they are encountered. The likelihood of buried objects, their nature and relative sizes, should be established by the site investigation. This task requires evaluation of information from a variety of sources including regional and site geology reports, geophysical surveys, borings, and test pits. Regional and site geology reports and land use records help to establish the likelihood and nature of buried objects. Geophysical surveys, borings, and test pits add detail and serve to verify preliminary conclusions drawn from these sources.

Claims have been made that microtunneling machines can be used in rock with unconfined compressive strengths of 30,000 psi or greater. Although encouraging advances are being made in rock-cutting, high-strength rock currently presents significant challenges to construction with microtunneling. The challenges include the need to apply high-thrust loads to the rock face so that the cutters can cause the rock to spall, and the need for high-thrust capacity cutters with bearings and mounting assemblies that are small enough to be fitted to a small-diameter machine head.

Site investigation strategy should focus on determining the depth and extent of rock, rock type, rock quality (weathering, jointing, and fracturing), hardness, stress state, strengths, and abrasiveness. For clay shales, slake durability and swelling tendencies should be determined. Reliable exploration and test methods are available for determining these characteristics.

The soft ground conditions that are most troublesome for microtunneling are essentially the same as those for larger tunnels. Raveling, flowing, or running ground, squeezing ground, swelling ground, and mixed face conditions present challenges to successful applications. The potential for these conditions must be determined to allow proper selection, configuration, and operation of the machine. These conditions, along with groundwater levels, establish the basis for selection of auger or slurry machines, selection of cutters for the head assembly, selection of overcut and lubrication, slurry characteristics, slurry separation equipment, auger pitch, and other important decisions.

The presence of contaminated groundwater or soil can dramatically increase the cost of a project depending on the types of contaminants identified and the extent of contamination. The potential for contaminants must be identified during the site investigation to avoid substantial increases in contract amounts due to changed conditions. All information on the types and levels of contamination should be presented to the contractor prior to bid. In addition, requirements for handling of contaminated soil and groundwater should also be presented to ensure that the contractor complies with all local, State, and Federal laws.

Existing site features that could be damaged by the construction or may impact the construction must be located and marked during the site investigation. Existing utilities may be located from as-built records, although locations of abandoned utilities are often not known. "Potholes" (i.e., shallow excavations made by auger boring, vacuum extraction, or manual excavation) should be used to confirm and mark locations of utilities that are near or intersected by the planned pipeline. Historic buildings and environmentally sensitive areas usually require evaluation on a case-by-case basis to ensure protection.

Once the microtunneling method has been chosen, several design considerations must be addressed. Machine selection includes the choice of a slurry or auger machine, and each machine can be fitted with a soft-ground, rock cutter, or combination cutter face. Estimated jacking loads must be determined to allow appropriate shaft spacing, interjack location, selection of pipe and jacking frame, design of thrust wall, sizing of overcut, and optimum lubrication. Based on estimated jacking loads, intermediate jacking stations which serve to distribute the load along the pipe string can be placed at appropriate locations. Machinery overcuts, typically 0.5 to 3 in. on the diameter, should be determined by analysis of soil conditions with proper consideration of pipe diameter, and caution should be exercised to ensure that the overcut is not too small, causing high jacking loads. Large settlements are generally not attributable to reasonable overcut space, but are almost always due to loss of stability at the face of the excavation. Lubrication, injected in the annular space created by the overcut, is generally recommended. Typically, bentonite or bentonite-polymer mixtures are used for lubrication purposes. Grouting the annular space after installation is most often ineffective unless voids exist around the pipeline. Excessive grouting pressures can result in migration of grout to unwanted locations.

Jacking and reception shafts are significant cost components in microtunneling projects. Proper shaft design is critical to microtunneling applications. The goal is to minimize the size and number of shafts, consistent with practical pipe length considerations and maximum practical spacings which will be limited by the strength of the laser, pumping capabilities of slurry machines, feasibility of interjack installation, jacking forces, torque capacity of auger machines, and production of heat in the heading. Shafts must be constructed with thrust walls properly designed to handle anticipated jacking loads with an appropriate safety factor. The design should take into account the design axial capacity of the pipe and the maximum thrust capacity of the jacking frame. Floor slabs should be poured independently of the thrust wall and should be finished to proper line and grade to avoid setup and steering problems during machine launch. The laser should be mounted independently of the thrust wall to avoid excessive movement during thrust-wall deflections under jacking loads. Groundwater and soil inflows into the shafts should be kept to an absolute minimum, with a watertight shaft being optimum (but not always practical), to avoid settlement, voids, steering, and safety problems. When groundwater is present, seals must be mounted to the shaft wall, and soils around the shaft must be stabilized to prevent soil and groundwater inflows during launch. The potential for bottom heave of the shaft should also be evaluated.

Current pipe materials used for microtunneling include concrete, vitrified clay, glass fiber-reinforced polyester resin (GFRP or Hobas), and steel. Important design characteristics that should be specified with allowable tolerances include straightness, roundness, diameter and wall thickness, squareness of ends, and proper jacking joint and spacer design. Every reasonable effort should be made to minimize the potential for misalignment, thrust-wall movement, abrupt steering corrections, pipe dimensions that are out of tolerance, or inadequate spacer/compression rings that can cause eccentric loading. Compression or spacer rings should be placed between pipe sections to distribute loads over the full end bearing area of the pipe section. However, it is unreasonable to ever assume that applied loads will be transferred down the pipeline without some eccentric loading. Therefore, an appropriate safety factor, ranging from 2 to 3 is generally recommended for pipe axial load design. Steerability of the pipe is dependent on allowable angular deflection of adjacent joints under given jacking loads. Concrete, clay, and GFRP have comparable steering capabilities; steel, with rigid joint connections, has much lower steerability.

Comprehensive bid documents help to eliminate claims during the construction process. Bid documents should include minimum performance requirements and the performance period. All site investigation data with interpretations should also be presented. Minimum qualifications of the prospective contractors should be specified and evaluated prior to bid. Minimum contractor submittal requirements should be outlined. All monitoring requirements for protection of existing utilities, site features, and structures should be identified. Requirements for establishing conditions existing before construction should be documented, to minimize frivolous claims and provide a rational basis for determining if damages have occurred as a result of the microtunneling project. A general framework for necessary remedial actions should be established in the event that construction does not proceed as planned. Measurement and payment should be clearly defined. Procedures for dispute resolution should be established to handle construction disputes in a timely manner.

Contractor submittals should include descriptions of the construction method, detailing the equipment, materials, shafts, dewatering system, thrust walls, pipe, and lubrication. Estimated jacking loads, as predicted by the contractor for each tunnel drive, should be submitted to the engineer. A sequence of operations with activity duration should be included with the submittal package. The contractor should submit qualifications of all key personnel, including specific microtunneling experience. Site layout at each shaft location should be detailed. Proposed drilling fluids and a spoil management and handling plan should be presented. The contractor should establish a quality assurance/control plan that will include a ground-movement monitoring plan prior to construction. Conditions existing prior to construction should be documented to serve as the baseline for determining the extent of any damages caused by the project. A safety plan, focusing on confined space entry, should be submitted for review. Detailed construction records, including machinery performance information such as jacking forces, machine torque, progression rates, pumping flow rates, lubrication, steering corrections, and machine locations, should be submitted on a daily basis during the microtunneling operations.

These guidelines are intended to help those who are relatively new to the process of designing and specifying projects using trenchless technology and are informative rather than prescriptive. The focus is on the equipment, materials, processes, applications, and potential difficulties. From these guidelines, the user should obtain an understanding of issues that should be considered and resources that are available for assisting in the design, specification, and construction of trenchless projects. While it is recognized that significant efforts are necessary by the owner and engineer to develop plans and specifications that are appropriate for a given set of project requirements and site conditions, these guidelines should assist the user in focusing that effort to ensure that all major issues are considered and addressed. Contractors should also benefit from the development of more uniform, carefully conceived designs, plans, and specifications developed from a rational set of guidelines that are based on sound engineering principles and supported by successful experience.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
Fahrenheit degrees	5/9	Celsius degrees or kelvin
feet	0.3048	meters
foot-pounds (force)	1.355818	meter-newtons or joules
gallons (U.S. liquid)	3.785412	cubic decimeters
inches	25.4	millimeters
pints (U.S. liquid)	0.4731765	cubic decimeters
pounds (force) per square inch	6.894757	kilopascal
pounds (mass)	0.4535924	kilograms
quarts (U.S. liquid)	0.9463529	cubic decimeters
tons (2,000 pounds, mass)	907.1875	kilograms

[1] To obtain Celsius © temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9)(F - 32). To obtain kelvin (K) readings, use: K = (5/9)(F - 32) + 273.15.

1 Introduction

1.1 Background

These guidelines mark the completion of the Construction Productivity Advancement Research (CPAR) project, "Trenchless Construction: Evaluation of Methods and Materials to Install and Rehabilitate Underground Utilities." CPAR is a cost-shared U.S. Army Corps of Engineers and construction industry research program. CPAR was created to help the U.S. construction industry improve productivity and regain its competitive edge by building on the foundation of the existing Corps research and development (R&D) programs and laboratory resources through the leveraging effect that cost-shared partnerships provide. The overall objective of the CPAR Program is to facilitate construction productivity improvements through cooperative R&D, field demonstrations, technology transfer, and commercialization.

Approximately 60 projects have been funded under the CPAR Program from its inception in 1989 through 1994 with the Corps providing over $25 million and the construction industry providing over $38 million in matching funds. This project was a joint effort conducted by the U.S. Army Engineer Waterways Experiment Station (WES) and the Trenchless Technology Center (TTC) at Louisiana Tech University.

1.2 Objective

The overall objective of this project was to develop guidelines that owners, engineers, and contractors could use to evaluate and select trenchless methods and equipment appropriate for their project requirements and site conditions.

1.3 Scope and Approach

These guidelines focus on the three major elements of trenchless technology that were investigated in this study: rehabilitation of existing pipelines using cured-in-place pipe (CIPP) and fold-and-formed pipe (FFP) methods, installation of small-diameter (2- to 10-in.) pipelines using mini-horizontal directional drilling (mini-HDD), and installation of larger diameter pipelines using microtunneling. The guidelines are based primarily on the results of extensive laboratory and field

investigations; the scope and potential impact of this test program exceeds any previous efforts. The guidelines are also based on state-of-the-art reviews, interviews with industry experts, and studies of case histories.

The guidelines are presented in a format patterned after that used for Corps of Engineers Guide Specifications, but with more detailed information presented. The intent is to make it relatively easy to develop project specifications using the information and references provided, by tailoring this to particular project requirements and site conditions.

2 Guidelines for Cured-in-Place Pipe (CIPP) and Fold-and-Formed Pipe (FFP)

2.1 Introduction

This report provides guidelines for the selection of all plant, materials, labor, and equipment needed and performance of all operations in connection with the rehabilitation of a subsurface pipeline by the cured-in-place pipe (CIPP) or fold-and-formed pipe (FFP) process. It is intended to help those who are relatively new to designing and specifying pipeline rehabilitation systems. The focus of this report is on the processes used, potential difficulties, and guidance for avoiding problems, as opposed to prescribed design procedures and specifications or even guide specifications. From this report, the engineer should obtain an understanding of what should be considered and resources for assisting in the design and specification of rehabilitation systems.

CIPP and FFP are pipeline rehabilitation techniques used to restore full service to a defective pipeline from access point to access point (typically a manhole). While CIPP can be used to rehabilitate a section of the pipeline as a point source repair, these guidelines address only complete rehabilitation. There are several rehabilitation systems in the market currently using CIPP, FFP, or related technologies.

2.1.1 Range of applications

CIPP and FFP systems can be used to eliminate or reduce inflow of storm water, infiltration of groundwater, exfiltration of pollutants, surface settlement caused by soil migration into the pipe, corrosive attack, and pipe irregularities/defects/joints in sewer collection systems. These systems can restore or increase hydraulic flow by smoothing surfaces. CIPP can be used in both circular and noncircular shapes.

While there are exceptions, CIPP and FFP techniques are normally preferred to rehabilitate pipelines under the following conditions:

a. The pipeline has adequate flow capacity during the expected life of the liner. (Note that reductions in infiltration and inflow after pipeline rehabilitation can actually lead to significant flow reductions over conditions that existed prior to rehabilitation.)

b. The pipe diameter and length of the rehabilitation run are within the general envelope of capabilities of the CIPP or FFP system as shown in Table 2-1.

c. Point source repairs are not practical because of economic, social, or environmental considerations, or if they cannot adequately rehabilitate the line segment.

d. The host pipe is not severely damaged, broken, or deformed. There are no flat surfaces or corners. There are no significant changes in pipe diameter from manhole to manhole. There are no sharp bends or tees. (Note: Liners may be used if special design considerations are given for these conditions. Also, use of CIPP liners may not be as severely restricted under these conditions as would be use of FFP liners.)

e. Flow bypassing is feasible or unnecessary due to low flows.

Table 2-1
Typical Range of Applications for CIPP and FFP

Method	Diameter Range	Maximum Installation Range	Liner Material	Applications	Minimum Design Life
CIPP	4 to 108 in.	1,000 to 3,000 ft	Thermosetting resin/fabric composite	Gravity and pressure pipelines	50 years
FFP	4 to 18 in.	500 to 700 ft	PVC, HDPE[1]	Gravity and pressure pipelines	50 years

[1] PVC = polyvinyl chloride; HDPE = high-density polyethylene.

2.1.2 Cured-in-place pipe (CIPP)

CIPP is a liquid thermosetting resin-saturated material that is inserted into the existing pipeline by hydrostatic inversion, air inversion, or mechanically pulling with a winch and cable. These installation techniques as used in current CIPP systems are illustrated in Figures 2-1 through 2-3. After insertion, the resin-saturated material cures by application of hot water or steam to form a new pipe of slightly smaller inside diameter, but of the same general shape as the original pipe. The liner is designed to fit snugly against the wall of the host pipe.

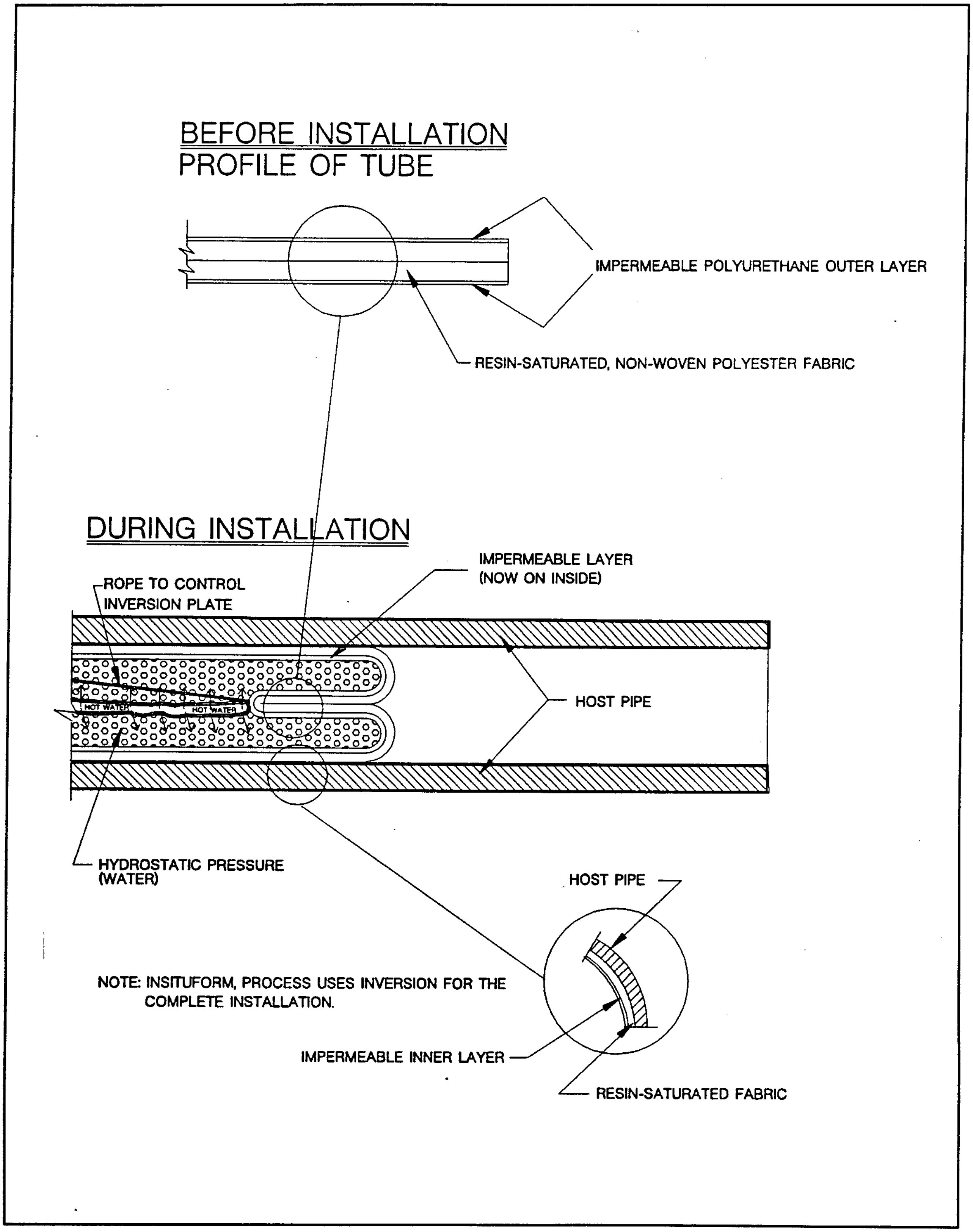

Figure 2-1. Typical CIPP installation by hydrostatic inversion (Insituform®)

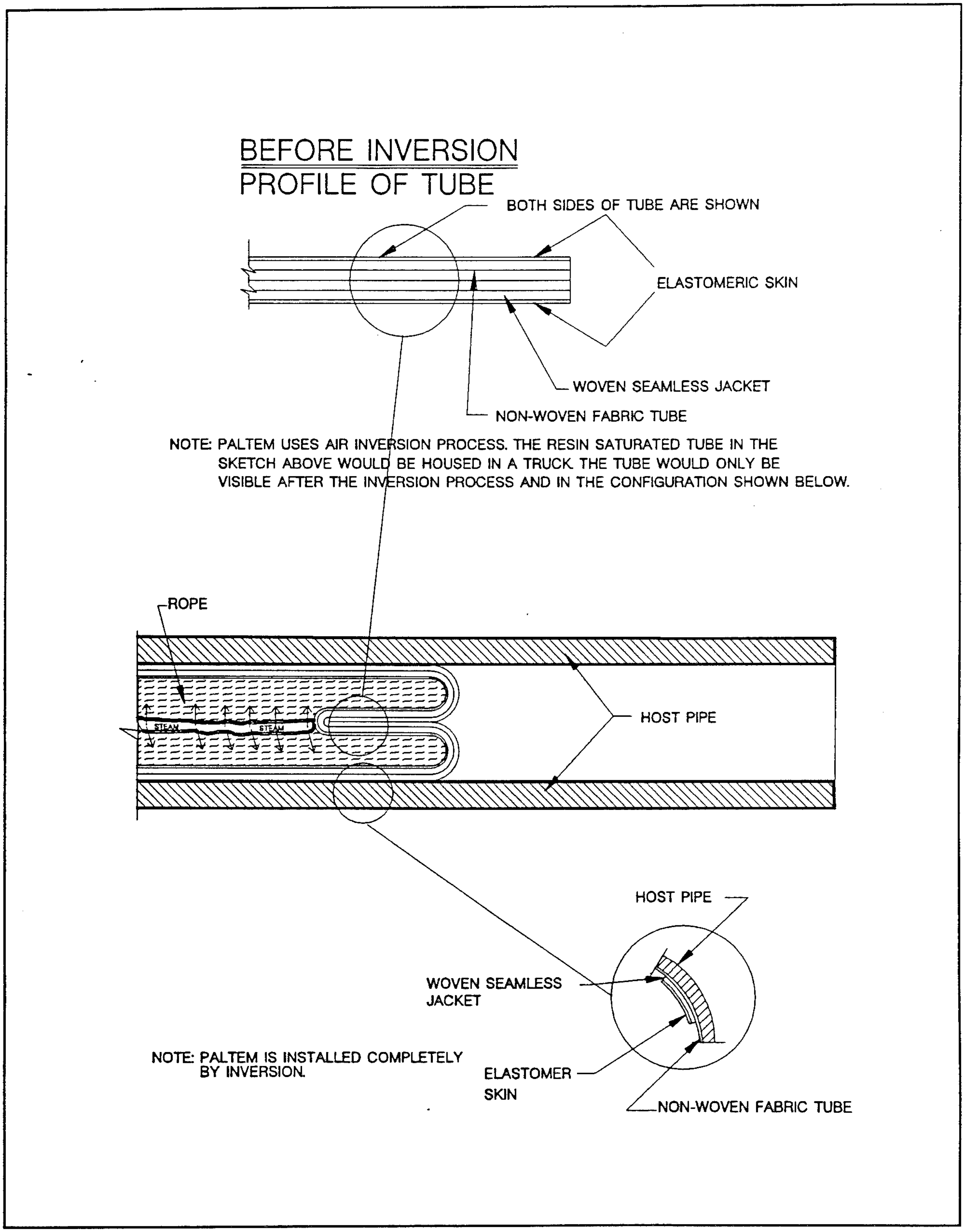

Figure 2-2. Typical CIPP installation by air inversion (Paltem HL®)

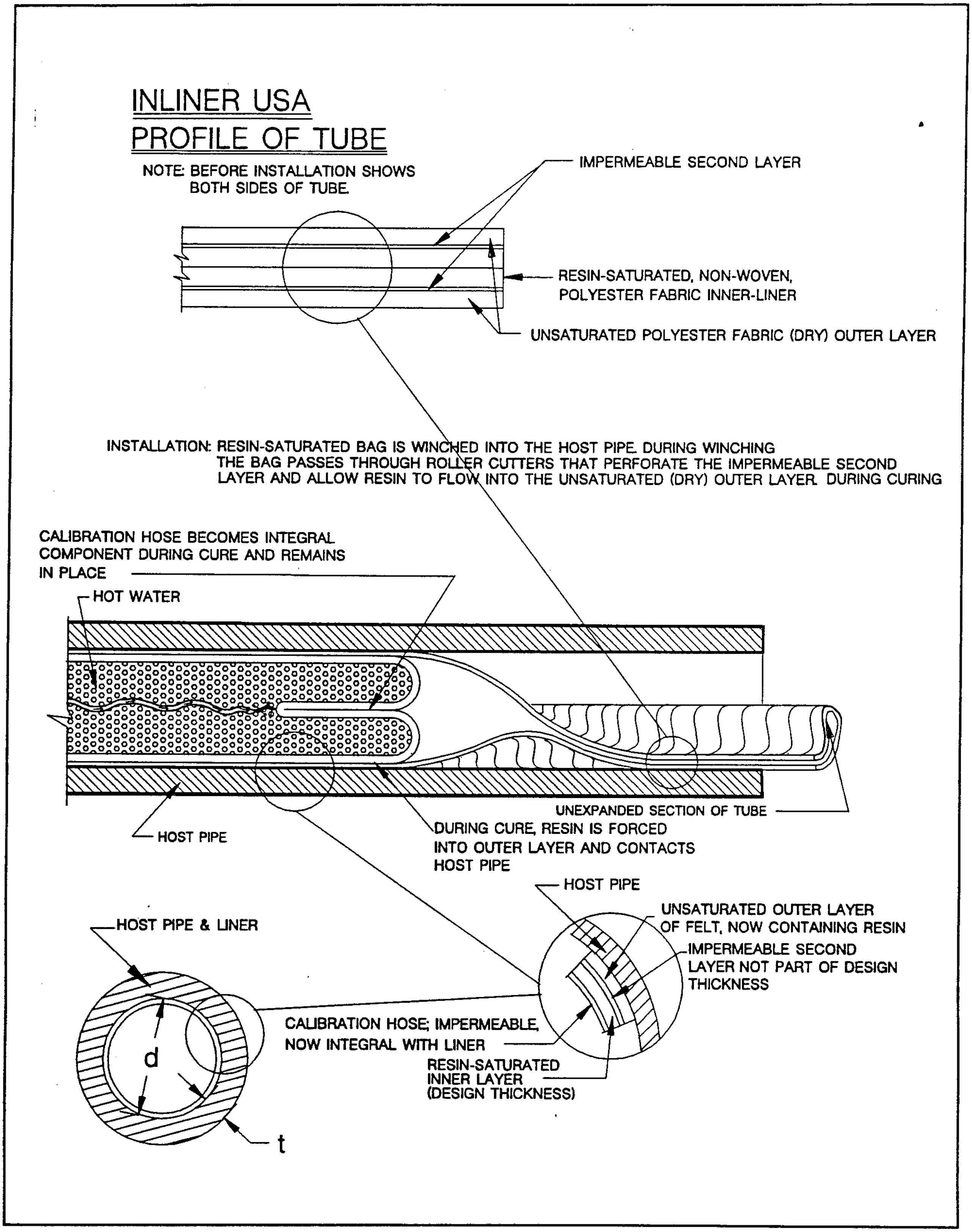

Figure 2-3. Typical CIPP installation by winching (In Liner USA®)

2.1.2.1 Basic components

The primary components of the CIPP are a flexible fabric tube and a thermosetting resin system. For typical CIPP applications, the resin is the primary structural component of the system. These resins generally fall into one of the following generic groups, each of which has distinct chemical resistance and structural properties. All have good chemical resistance to domestic sewage. The three primary resin systems used are unsaturated polyester, vinyl ester, and epoxy. Unsaturated polyester resins were originally selected for the first CIPP installations due to their chemical resistance to municipal sewage, good physical properties in a CIPP composite, excellent working characteristics for CIPP installation procedures, and economic feasibility. Unsaturated polyester resins have remained the most widely used systems for the CIPP processes for over two decades. However, at least one manufacturer currently uses vinyl ester resins for all applications.

Vinyl ester and epoxy resin systems are mainly used in industrial and pressure pipeline applications where their special corrosion and/or solvent resistance and higher temperature performance are needed and higher cost justified. In drinking water pipelines, epoxy resins are required.

The primary function of the fabric tube is to carry and support the resin until it is in place in the existing pipe and is cured. This process requires that the fabric tube withstand installation stresses with a controlled amount of stretch but with enough flexibility to dimple at lateral service connections and expand to fit against existing pipeline irregularities. The fabric tube material can be woven or non-woven, with the most common material being a non-woven needled felt. It can consist of one or more layers of felt, glass fiber composite cloth, impermeable plastic, and other materials to form the total liner thickness. Impermeable plastic coatings are commonly used on the interior and/or exterior of the fabric tube to protect the resin during installation. The layers of the fabric tube can be seamless, as with some woven materials, or longitudinally joined with stitching or heat bonding.

There are many CIPP systems in the market today. The primary differences between these various CIPP systems are in the composition and structure of the tube, method of resin impregnation (by hand or by vacuum), installation procedure, and curing process.

2.1.2.2 CIPP method description

First the existing pipe is thoroughly cleaned and internally inspected to assess existing conditions. The distance between inspection manholes is measured, and all damaged sections and service inlets are carefully noted. The purchase order placed with the CIPP manufacturer is based on these data, and the product is manufactured for insertion into a particular pipe.

Roots, grease, sediment, and debris are removed from the line. In the inversion method, the inversion head usually overcomes external water pressure, and incoming water is pushed ahead of the inverting tube so all water is expelled and none is trapped. If necessary, spot repairs may be performed prior to liner placement, and a preliner may be used if excessive filtration is evident.

After the pipeline has been cleaned, inspected, and the flow has been bypassed, the flexible fabric tube is inserted into the pipe through a manhole or another convenient entry point. Just before the installation, the flexible tube is impregnated (wetted-out) with the liquid thermosetting resin at the contractor's wet-out facility or, for large-diameter tubes, at the jobsite. It is critical that the fabric tube is totally saturated and air evacuated in order to provide consistent finished

physical properties required by design. This flexible tube is installed in the old pipe by winching mechanically or inverting it under air or water pressure.

In the inversion process, the tube is cuffed back and clamped to an inversion ring at the access point. The tube is then fed through the ring with the tube being turned inside out. Water or air pressure is then applied to continue turning the tube inside out, pushing it through the existing pipe. The pressure keeps the tube expanded against the existing pipe wall as it inverts along the installation length. With the winched technique, the wet-out tube is pulled through the full length of the existing pipe. Then an inflation bladder is inverted through the tube to expand it against the host pipe wall. Combinations and variations of these two methods are used by most CIPP systems.

Once the tube is inserted into the existing pipe and expanded, heated water or steam is circulated through the tube to initiate the curing or hardening of the thermosetting resin. This changes the resin from a liquid to a solid. After the curing cycle is complete, the CIPP is cooled and a new pipe is formed with a slightly smaller inside diameter, but of the same general shape as the original pipe.

The ends of the cured pipe are then trimmed, forming a smooth, seamless CIPP. At the service connections or laterals, dimples are normally created due to the applied pressure. In the case of pipes large enough for personnel entry, a special cutting device is used to reopen service connections at the dimple locations. In pipes that are too small for personnel entry, a robot is used in conjunction with a closed-circuit television (CCTV) camera to locate the dimples visually and reopen the service connections.

2.1.2.3 Advantages

There are several advantages of the CIPP method over other methods of trenchless pipeline rehabilitation. Grouting is not normally required due to the tight fit of the CIPP against the existing pipe. The CIPP has no joints and has a very smooth interior surface which typically improves flow capacity, despite the slight decrease in diameter. Noncircular shapes can be accommodated often without a decrease in flow capacity. The lining is capable of accommodating bends and some existing pipe deformations. Entry is possible via existing manholes or through minor excavations, and the total installation can take place rapidly. Remote-control internal lateral connection is possible. The cost of CIPP has been found to be competitive with all other methods of construction and rehabilitation, particularly for larger projects with multiple segments and where social and environmental considerations are significant.

2.1.2.4 Disadvantages

Compared with other rehabilitation techniques, CIPP liners require expertise to ensure that installations result in a quality product. A trained crew and operators with special equipment are required, which may cost more for small jobs. High set-up costs on small projects may reduce the cost effectiveness of this method. The tube or hose must be specially constructed for each project (some manufacturers provide stock materials to their licensees for small diameters, such as 8, 10, and 12 in.). The existing flow must be bypassed or plugged upstream of the section to be rehabilitated during the installation process. Sealing may be required at liner ends or cuts to prevent inflow or outflow. The curing period could take 5 hr or more under certain circumstances. The rehabilitated pipe will take the shape of the host pipe, including deformations.

2.1.3 Fold-and-formed pipe (FFP)

The FFP process makes use of a thermoplastic (HDPE or PVC) pipe that is folded or deformed to reduce the cross-sectional area. The pipe is manufactured by extruding in either a folded form or a circular form which is later folded thermo-mechanically. The folded pipe is rolled onto a spool for transport to the jobsite. It is then pulled into place and expanded and rounded to conform to the internal shape and size of the existing pipe by heat and pressure.

2.1.3.1 FFP method description

Before the installation can begin, incoming flow to the pipe section must be eliminated or reduced to a minimum. This is typically accomplished by using one of the following techniques: (a) bypass pumping, (b) plugging upstream lines, or (c) diversion to an adjacent system. Since the installation is rapid and involves primarily small-diameter pipes, the plugging of upstream lines is often the method chosen. The upstream system acts as a storage basin for the flow until the installation is complete.

The line is cleaned to remove roots, grease, sediment, and debris. If necessary, spot repairs are performed prior to liner placement. If there is moderate to excessive infiltration, it may be necessary to use a preliner or to seal the affected pipe openings using standard grouting procedures. Once the pipe is cleaned and prepared, the folded liner is pulled through the host pipe. Some manufacturers preheat the folded liner material until it is flexible before pulling it into the host pipe. Because the liner is folded and flexible, there is little or no stress created in either the host pipe or FFP.

Prior to rounding, the FFP is heated internally to create a uniform temperature throughout the material. For one system, a special rounding device is then inserted in the upstream end of the FFP and propelled by steam pressure to the downstream termination point. As the rounding device progresses, it expands the FFP tight against the walls of the host pipe. Other systems use only heat and pressure to round the FFP. Any liquids in the host pipe are pushed out ahead of the expanding liner. The flexible FFP molds to the shape of the host pipe and normally forms distinct dimples at service connections.

Pressure is maintained in the rounded FFP until it cools to a rigid state. To complete the installation, the ends of the FFP are cutoff, and laterals are reopened by a remote-controlled cutter from within the reconstructed pipeline. A FFP rehabilitation can normally be performed by a crew of four to five persons in approximately 5 hr.

2.1.3.2 Advantages

The fold-and-formed method provides a continuous pipe without joints and excellent flow characteristics because the reduction in pipe diameter is minimal. Very little, if any, flow capacity reduction occurs. This method eliminates infiltration at the joints. Chemical grouting is required only at lateral openings and liner ends. Internal lateral connection is possible, and the installation method is fast. This method typically leaves a very small annular space.

2.1.3.3 Disadvantages

Possible structural damage (collapse/misalignment) of the existing pipe can cause problems. The installation lengths are limited due to the required pull-in forces and the capacity to heat the entire length of the line during rounding/forming. The installation length limitation is typically up to 700 ft depending on the diameter of the pipe. The diameter range (4 to 18 in.) to which the folded pipe may be manufactured also limits the application of this method. Pipe flow must be discontinued during the installation process.

2.2 Applicable References

Numerous associations and organizations have published documents that should assist in the development of specifications for pipeline rehabilitation. Listed below are a number of these references, standards, guidelines, and model specifications. This list is not intended to be exhaustive, but is intended to identify some of the most recent and commonly used references. There are times when specifications may override referenced standards, and a statement regarding the governance of the specifications on such occasions should be included.

2.2.1 American Society for Testing and Materials (ASTM) Standards

(Unless otherwise noted, all ASTM Standards should be for the latest year of publication.)

ASTM C 581	Determining Chemical Resistance of Thermosetting Resins Used in Glass-Fiber-Reinforced Structures Intended for Liquid Service. *(Standard Practice)*
ASTM D 543	Resistance of Plastics to Chemical Reagents. *(Test Method)*
ASTM D 638	Tensile Properties of Plastics. *(Test Method)*
ASTM D 695	Compressive Properties of Rigid Plastics. *(Test Method)*
ASTM D 790	Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. *(Test Method)*
ASTM D 883	Definitions of Terms Relating to Plastics. *(Definition)*
ASTM D 1248	Polyethylene Plastic Molding and Extrusion Materials. *(Specification)*
ASTM D 1598	Time-to-Failure of Plastic Pipe Under Constant Internal Pressure. *(Test Method)*
ASTM D 1600	Terminology Relating to Abbreviations, Acronyms and Codes for Terms Relating to Plastics. *(Abbreviations Specification)*
ASTM D 1693	Environmental Stress-Cracking of Ethylene Plastics. *(Test Method)*

ASTM D 1784	Rigid Poly (Vinyl Chloride) (PVC) Compound and Chlorinated Poly (Vinyl Chloride) (CPVC) Compounds. *(Specification)*
ASTM D 2122	Determining Dimensions of Thermoplastic Pipe and Fittings. *(Test Method)*
ASTM D 2290	Apparent Tensile Strength or Tubular Plastics and Reinforced Plastics by Split-Disk Method. *(Test Method)*
ASTM D 2412	Determination of Characteristics of Plastic Pipe by Parallel-Plate Loading. *(Test Method)*
ASTM D 2837	Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials. *(Test Method)*
ASTM D 2992	Obtaining Hydrostatic or Pressure Design Basis for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings. *(Practice)*
ASTM D 3034	Type PSM Poly (Vinyl Chloride) (PVC) Sewer Pipe and Fittings. *(Specification)*
ASTM D 3262	"Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Sewer Pipe. *(Specification)*
ASTM D 3350	Polyethylene Plastic Pipe and Fitting Materials. *(Specification)*
ASTM D 3567	Determining Dimensions of Reinforced Thermosetting Resin Pipe (RTRP) and Fittings. *(Practice)*
ASTM D 3681	Chemical Resistance of Reinforced Thermosetting Resin Pipe in a Deflected Condition. *(Test Method)*
ASTM D 3839	Underground Installation of Fiberglass (Glass-Fiber-Reinforced Thermosetting Resin) Pipe. *(Practice)*
ASTM F 412	Terminology Relating to Plastic Piping Systems. *(Definition)*
ASTM F 1216	Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube. *(Practice)*
ASTM F 1504	Folded PVC Pipe for Existing Sewer and Conduit Rehabilitation. *(Specification)*
ASTM F 1533	Deformed Polyethylene Liner. *(Specification)*

2.2.2 Other guidance

Several related books, manuals, and related materials have been published that may be useful in gaining a better understanding of the pipeline rehabilitation and construction processes. The following documents are available from the specified sources. However, the inclusion of a reference in this report is not an indication of an endorsement of its contents.

2.2.2.1 American Society of Civil Engineers (ASCE)

Design and Construction of Sanitary and Storm Sewers, 1969.

Gravity Sanitary Sewer Design and Construction, 1982.

Gravity Flow Pipe Design Charts, 1987.

Tables for the Hydraulic Design of Pipes and Sewers, Fifth Edition, 1990.

Pressure Pipeline Design for Water and Wastewater, Second Edition, 1992.

Existing Sewer Evaluation and Rehabilitation, 1994.

2.2.2.2 American Water Works Association (AWWA) and AWWA Research Foundation

Assessment of Existing and Developing Water Main Rehabilitation Practices, 1990.

AWWA Standard for Fiberglass Pressure Pipe, ANSI/AWWA C 950-88, 1989.

Water Utility Experience With Plastic Service Lines, AWWA Research Foundation, 1992.

2.2.2.3 National Association of Sewer Service Companies (NASSCO)

A Manual of Practice for Pipeline Analysis, Evaluation, and Rehabilitation, 1995.

Specification Guidelines for Sewer Collection System Maintenance and Rehabilitation, Eighth Edition, 1994.

Inspector Handbook for Sewer Collection System Rehabilitation.

2.2.2.4 National Sanitation Foundation (NSF)

Standard No. 14 - Plastics Piping System Components and Related Materials, 1988.

2.2.2.5 Plastics Pipe Institute (PPI)

Pipeline Rehabilitation with Polyethylene Pipe, 1988.

Standards for Plastic Piping, 1990.

2.2.2.6 Trenchless Technology Center (TTC)

Guice, L. K., Straughan, T., Norris, C. R., and Bennett, R. D. (1994). *Long-Term Structural Behavior of Pipeline Rehabilitation Systems.*

Najafi, Mohammed. (1994). *Trenchless Pipeline Rehabilitation: State-of-the-Art Review.*

2.2.2.7 Water Environment Federation (WEF)

(Note: Some of the references listed in the ASCE section are also available through the WEF.)

Guidelines for Inspection and Maintenance of Wastewater Collection Systems.

2.2.2.8 Water Research Center (WRC)

Sewerage Rehabilitation Manual, Second Edition, 1983.

2.2.3 Major organizations associated with pipeline rehabilitation

Several organizations have pipeline-rehabilitation-related references other than those cited previously. Additional information can be obtained by contacting the following organizations.

2.2.3.1 Associated General Contractors of America (AGC)
1957 E. Street, NW
Washington, DC 20006
Phone: 203-974-0800

2.2.3.2 American Society of Civil Engineers (ASCE)
P.O. Box 831
Somerset, NJ 08875-0831
Phone: 212-705-7300

2.2.3.3 American Public Works Association (APWA)
106 W. 11th Street, Suite 1800
Kansas City, MO 64105-1806
Phone: 816-472-6100

2.2.3.4 American Underground Space Association (AUA)
511 11th Avenue South, Box 320
Minneapolis, MN 55415
Phone: 612-339-5403

2.2.3.5 American Water Works Association (AWWA)
6666 W. Quincy Avenue
Denver, CO 80235
Phone: 303-795-2449

2.2.3.6 National Association of Sewer Service Companies (NASSCO)
101 Wymore Road, Suite 521
Altamonte, FL 32714
Phone: 407-774-0304

2.2.3.7 North American Society for Trenchless Technology (NASTT)
435 North Michigan Ave, Suite 1717
Chicago, IL 60611-4067
Phone: 312-644-0828

2.2.3.8 National Utility Contractors Association (NUCA)

4301 N. Fairfax Drive, Suite 360
Arlington, VA 22203-1627
Phone: 703-358-9300

2.2.3.9 Plastics Pipe Institute (PPI)
Wayne Interchange Plaza II
155 Route 46 West
Wayne, NJ 07470
Phone: 202-371-5306

2.2.3.10 Trenchless Technology Center (TTC)
College of Engineering
Louisiana Tech University
Ruston, LA 71272
Phone: 318-257-4072

2.2.3.11 Water Environment Federation (WEF)
601 Wythe Street
Alexandria, VA 22314-1994
Phone: 703-684-2400

2.2.3.12 Water Research Center (WRC)
2655 Philmont Avenue
Huntingdon Valley, PA 19006
Phone: 215-938-8444

Franklin Road, Blagrove, P.O. Box 85
Swindon, Wiltshire, UK SN5 8YR
Phone: 0793-488301

2.3 Sewer System Evaluation

One of the most important steps in selecting a rehabilitation system is to conduct a thorough evaluation of the sewer system including assessments of the infiltration and inflow (I/I), the structural condition, and the hydraulic condition. A sewer system evaluation and survey (SSES) is necessary to identify and quantify sources of I/I so that the most appropriate rehabilitation plan to achieve significant reductions in I/I can be recommended. Without such a survey, a rehabilitation effort might result in a disparity between anticipated and actual reduction of I/I. This section includes an overview of the basic steps through which a total sewer system evaluation is accomplished and where additional guidance on performing an evaluation can be found.

2.3.1 General

The steps necessary in the evaluation of a sewer system for rehabilitation include:

a. Preliminary analysis of the sewer system.

b. Structural analysis.

c. Hydraulic analysis.

d. Infiltration and inflow (I/I) analysis.

e. Sewer system evaluation and survey (SSES).

Each of these steps plays a role in an end goal of knowing the status of the sewer line, quantifying the amount of I/I which is present on a source-by-source basis, deciding whether rehabilitation is required and/or economically justified at this time and devising a plan for the rehabilitation of the sewer.

2.3.2 Definitions

a. *Infiltration.* The water entering the sewerage system by means of groundwater leakage from connections, joints, manhole walls, or defective pipes.

b. *Inflow.* The water entering the system from storm water sources to include manhole covers, roof leaders, drains (cellar, area, yard, and foundation), cross connections from storm and combined sewers, catch basins, and surface runoff.

c. *Excessive I/I.* Those quantities of I/I which can be economically eliminated from a sewer system by repair or rehabilitation.

2.3.3 Structural evaluation of the sewer line

The objective of the structural evaluation is to determine if the pipe needs to be replaced or rehabilitated from the structural point of view. The structural evaluation is conducted by physical inspection in case of personnel entry or by CCTV inspection. The inspection should determine the location, nature, type, size, cause, etc., of each structural defect along the pipeline.

Structural defects may result from poor design, poor construction, corrosion, or age deterioration. The structural defects from poor design may be caused by specifying incorrect bedding or joint type, underestimating the expected loads on the pipe, differential settlement, high sulfide and corrosive formation in the wastewater, etc. The defects due to poor construction may result from disturbed subgrade, uncompacted bedding and/or backfill, misalignment, incorrect grout, tar, gasket, or cracked joints, etc. The rate of deterioration can be accelerated and can lead to structural failure depending on the soil type, interior hydraulic conditions, groundwater level and fluctuation, and loads on sewer.

When corrosion is the reason for the structural defects, the source must be identified; the corrosive material must be removed or neutralized through cleaning, and the corrodible sections of the pipe must be protected in the rehabilitation phase.

The stability of flexible and deteriorated pipes depends on lateral support from adjacent soils. Therefore, it is very important to understand the interaction between the sewer and the surrounding soils during the structural evaluation of the sewer line.

The most common materials used in old sewer lines are brick, plain concrete, or vitrified clay. Joints were usually grouted with cement mortar, which could not accommodate differential settlement, erosion, or corrosion. The structural defects in brick sewers could be in the form of missing mortar or brick, loose bricks, vertical and lateral deflections, soft mortar, root intrusion, and protruding laterals. Brick sewers depend on lateral support from adjacent soil, and when the adjacent soil is loose, deterioration accelerates. The structural defects in concrete and clay pipe could be in the form of longitudinal, circumferential, or multiple deflection cracks, collapsed pipes, holes in the wall, open or cracked joints, root intrusion, corrosion, protruding laterals, and protruding joint materials.

Many concrete and clay sewers continue to function even with critical structural defects. However, the pipeline will continue to deteriorate depending on the condition and the internal or external environment. The soil structure above the pipe could eventually collapse, depending on the magnitude of the problem.

Pipeline investigation should help determine the possible causes of failure. Eliminating causes through the analysis will reduce the list to a manageable size for continued study. Soil borings, wastewater analysis, pipe-crown or manhole-wall pH determination, pipe-wall structural analysis, and pipe-soil interaction analysis provide technical information needed to determine causes and develop remedies.

Some rehabilitation techniques are more effective in dealing with certain types of failure than others. Rehabilitation that addresses failure symptoms without considering failure mechanisms invites costly errors. Through a staged screening process, the applicability of repair methods should be assessed in relation to special construction problems, sizes, and shapes of existing pipes, pipe conditions to be corrected, and desired capacities of the rehabilitated system. Significant differences in the capabilities of the rehabilitation methods will significantly reduce the field of alternatives. Based on the sewer assessment, corrective actions may include:

a. Monitoring and collecting information.

b. Stabilization or point repair.

c. Rehabilitation.

d. Replacement.

Monitoring and collecting information is selected when the sewer line is in an early stage of deterioration and it is feasible to defer rehabilitation. A program of monitoring and collecting information should continue until the monitoring indicates the need for stabilization or lining. The frequency of the inspection is based on the conditions of the sewer.

Stabilization or point repair can extend the useful life of the sewer. Point repair can be achieved by grouting the fractured or weak area, lining a pipe joint, or replacing a seriously fractured joint between two manholes. The grouting can be done manually if the pipe is accessible for personnel entry, or it can be done with remote-control robotic devices. Grouting can also be used to stabilize the surrounding soils around the pipe. The soil grout can be cement or chemical grout and can be injected from inside the pipe or from borings.

Rehabilitation may be accomplished by lining the whole reach from manhole to manhole. Lining may be preceded with grouting holes or cracks and stabilizing the surrounding soil, if needed. The liner could have a thin or thick wall depending on the extent of structural deterioration of the host pipe. Replacement is indicated if the pipeline is deteriorated beyond repair using rehabilitation methods.

2.3.4 Hydraulic assessment of the sewer line

Hydraulic assessment involves the investigation of the hydraulic performance of the sewer system and of the critical sewers. The assessment basically compares the estimated maximum discharge in the future along the expected life of the rehabilitated sewer with the potential capacity of the system.

For the future needs of the system to be estimated, data must be collected on the expected population, usage rates, potential growth of industrial and commercial facilities, etc. The sewer system is modeled, and the flow discharge expected for every sewer line is calculated. Critical sewers and collection systems should be modeled in more detail. Computer modeling may prove to be beneficial. The system capacity can be calculated from the pipe diameters and invert elevation data obtained from the as-built construction drawings and field measurements. Actual flow is measured to confirm the calculated flow and to isolate the I/I flow from the wastewater flow. Flow is measured at different times, at peak and minimum flows, and after heavy rain during the rainy season. Based on this information, the I/I flow is calculated, and the sewage flow is determined. The total measured flow will confirm the calculated system capacity.

The decision for rehabilitation or replacement of the line should be based on comparison of the system capacity and the expected maximum discharge during the expected life of the line. If the capacity of the sewer line is greater than or equal to the maximum expected discharge, then rehabilitation is the solution. If the capacity of the sewer line is less than the maximum expected discharge, then replacement is the solution. Another potential solution may be rehabilitating the sewer line and installing a new small line to take the extra flow when the extra flow is encountered.

2.3.5 Objectives of the SSES

The objectives of the SSES report are to:

a. Establish and quantify the type, location, and flow rate of each significant I/I source.

b. Estimate the cost of eliminating or reducing each source.

c. Compare costs associated with flow reduction with those for transport and treatment.

d. Determine if I/I intrusion is excessive or nonexcessive according to PL 92-500 and U.S. Environmental Protection Agency (EPA) regulations.

2.3.6 Steps in conducting a SSES

2.3.6.1 Physical survey

2.3.6.1.1 *Aboveground inspection.* For an aboveground inspection, sanitary sewer maps and storm sewer maps should be compiled prior to commencement. As-built drawings are preferred since they indicate grades and types of materials used. The aboveground inspection should be conducted in such a way that the general conditions of the area are noted to include streets, major structures, topography, manholes, waterways, etc. After the general conditions are noted, all problem areas should be identified, including manholes with inadequate access, buried structures, and utility and traffic interferences. All inflow sources should then be identified. These include, but are not limited to, low or inundated manhole covers, roof leaders, area drains, catch basins, foundation drains, and creeks. Using the sanitary and storm sewer maps, all I/I sources should then be checked for proximity and adequacy, and rainfall simulation tests should then be planned for all areas that are deemed inadequate. Also, plans should be made to uncover manholes and raise the frames to above grade.

2.3.6.1.2 *Manhole inspection.* Manholes should be inspected to determine the general condition of the sewers. In addition, the conditions of the lines as well as I/I sources should be noted. From this information, the areas of the sewer that need internal inspection can be identified. In selected manholes, depth of flow readings should be correlated with the length, size, type, and general conditions of the sewer line to get a preliminary idea of how much I/I is present in the sewer system.

2.3.6.2 Inflow investigation

2.3.6.2.1 *Flow monitoring.* Once the possible rehabilitation areas have been identified from the physical survey, flow monitoring should be conducted to further determine the extent of the I/I. Flow monitoring should be conducted during high groundwater events for infiltration purposes as well as during storm events for inflow. Dry weather measurements should also be taken and comparisons made. These readings should all be taken during the early morning hours (2 to 4 a.m.) to separate I/I flows from normal sanitary flows.

2.3.6.2.2 *Smoke testing.* Smoke testing is an inexpensive and timely way to detect inflow sources in sewer lines. Smoke testing should be conducted on a calm day and only when soil conditions above pipes are not saturated, frozen, or snow covered. Also, sewer lines that contain sags or are

at full flow should not be tested. The tests should be conducted only in lines that have been previously assessed by inspection and flow monitoring. Residents as well as the fire department should be given ample notification prior to testing. All smoke emissions should be noted in reports with written descriptions, videotape, and pictures. Based upon the smoke test results, visual inspection of manholes believed to have direct inflow connections into sanitary sewers should be conducted. In addition, identification of direct inflow sources as well as cross-connections between sanitary and storm systems must be noted. Experience has shown that smoke testing is most effective in revealing lateral service line problems.

2.3.6.2.3 *Dyed water testing.* Infiltration and inflow can be detected using dyed water testing. Fluorescent dyes which are nonreactive with the environment, as well as biodegradable should be used for the following procedures:

a. Based upon the results of the smoke tests, the areas of the storm sewer that run parallel to sanitary lines and cross connections between lines should be plugged, then flooded with dyed water.

b. Upon completion of the previous step, catch basins, ditches, pond areas, and footing drains should then be flooded with dyed water, to allow detection of inflow as well as infiltration through the soil.

Upon completion of these procedures, downstream manholes should be checked for the presence or absence of dye. From the amount of dye and the time required for the dye to reach the downstream manhole, further decisions can be made about which sections of sewer pipe need to be cleaned and inspected.

2.3.6.3 Preparatory cleaning

The lines must be cleaned prior to inspection to determine all structural problems and I/I sources. Since pipes are normally inspected with CCTV, they must be free from all debris to include grease accumulations, roots, sludge, mud, sand, gravel, and bricks. This cleaning should be done immediately prior to inspection and should be coordinated to utilize proper equipment and disposal sites. Also, any problem areas or connections that could possibly interfere with cameras and/or physical inspection should be noted.

2.3.6.4 Internal inspection

Internal inspection preparation includes determining what method of inspection is feasible and obtaining the proper equipment. Just prior to inspection, all storm sewers within the area which were identified as potential inflow sources may be flooded. After this is completed, either of the following two methods is appropriate.

2.3.6.4.1 *Physical inspection.* If sewage lines are large enough, not in service, and properly ventilated, then actual physical inspection can be conducted according to National Institute of Safety and Health-Occupational Safety and Health Act (NIOSH-OSHA) safety practices and procedures. The inspector should document all structural problems as well as attempt to quantify I/I intrusions. It should be noted that a large sewer not in service is normally not a good candidate for rehabilitation.

2.3.6.4.2 *CCTV inspection.* A camera with light source mounted in a protective container is pulled through the sewer line on cables or is self-propelled. This camera provides videotape documentation of the interior of the pipe, which is used to quantify the I/I and assess structural problems. After CCTV inspection, the inspector should attempt to detect any illegal connections which may be adding to the I/I problem.

2.3.6.5 Cost-effectiveness analysis

There are many methods for determining the cost effectiveness of a rehabilitation program. Table 2-2 provides guidance for rehabilitation of defects in the pipeline. Generally, these methods entail quantifying the cost of reduction of I/I for each rehabilitation method and then selecting the alternative with the highest benefit/cost ratio. The reduction of treatment costs due to reduced I/I is a direct benefit and should be factored into the analysis. Based upon the assessment of the sewer system, a decision must be made about the most cost-effective rehabilitation method for each of the I/I sources identified as excessive. If I/I cannot be handled by the present system, it can be transported and treated elsewhere. This cost alternative should always be considered.

After method selection, the work must be prioritized by cost and severity of problem to come up with a plan for rehabilitation. In determining cost effectiveness, all methods should be compared using present worth analysis. The least cost rehabilitation method should be selected unless the costs are within 10 percent of one another. If costs are within 10 percent, then the alternative with the longest expected service life should be chosen.

Social costs are not explicitly considered in current methods of analysis and do not show up in the actual bid price. These costs include disruptions to surface traffic and businesses, potential for increased accidents, and increased pollution. The explicit inclusion of social costs is an issue that deserves consideration. However, current methods for analyzing benefits and costs are not amenable to this task.

2.3.7 SSES in small cities

In many small cities, funds to execute all the phases of SSES are not available. Therefore, these communities typically do not evaluate their sewer system before rehabilitation. This practice is not recommended in rehabilitation. If the owner decides to rehabilitate the sewer system without an SSES, the owner is advised to execute the affordable phases of the SSES in their budget. The following phases (discussed previously) could be conducted without high expenditure:

a. Evaluation of the repair and maintenance records to identify the locations of repetitive leakage and repair.

b. Aboveground inspection.

c. Manhole inspection.

d. Flow monitoring.

e. Smoke test.

f. Dyed-water test.

Table 2-2
Guidance for Rehabilitation of Pipelines (*Trenchless Technology* 1994)

Defect	Pipe Diameter (in.)	Appropriate Rehabilitation Method	Description
Roots, light	6-12	Chemical treatment	Foam fill
Roots, light	15-30	Chemical treatment	Foam spray
Roots, heavy	4-6	Cleaning	Cable machine
Roots, heavy	8-12	Cleaning	Rodding machine
Roots, heavy	15-36	Cleaning	Bucket machine
Debris on invert, light	6-24	Cleaning	Jet machine
Debris on invert, light	18-36	Cleaning	Special jet nozzles
Debris on invert, light	18-36	Cleaning	Cleaning ball
Debris and grease, heavy	6-12	Cleaning	Jet machine
Debris and grease, heavy	8-15	Cleaning	Rodding machine
Debris and grease, heavy	15-36	Cleaning	Bucket machine
Debris and grease, heavy	24-96	Cleaning	Live Line Ltd.
Infiltrating joints	6-30	Sealing, lining	Chemical grout
Infiltrating joints	36-96	Sealing, lining	Chemical grout, CIPP
Infiltrating joints and service	6-12	Sealing, line section	Flooding method
Broken pipe, minimum amount	6-96	Point repair	Excavation or robotic
Broken pipe, moderate amount	6-24	Point repair	CIPP
Broken pipe, moderate amount	6-30	Robotics repair	Epoxy injection
Broken pipe, moderate amount	6-30	Robotics repair	Steel Sleeve
Broken pipe, extensive amount	6-96	Pipe lining, point repair	Various methods
Broken pipe, extensive amount	42-96	Pipe lining, point repair	Various methods
Misalignment and movement	6-96	Pipe lining	Various methods
Misalignment and movement	42-96	Pipe lining, man-entry	Various methods
Corrosion	6-96	Pipe lining	Various methods
Corrosion	42-96	Pipe lining, man-entry	Various methods
Corrosion	42-96	Spray, man-entry	Epoxy
Collapsed pipe, minimum amount	6-96	Point repair	Excavation
Collapsed pipe, moderate amount	6-18	Slipline	Pipe bursting, pipe lining
Collapsed pipe, extensive amount	6-96	Replacement	Excavation

After as many as possible of the phases of the SSES are performed, the problem of locating the possible sources of infiltration or inflow can be cost effectively minimized, and the priorities and methods of rehabilitation can be identified. The costs of portions of the SSES not performed may then be transferred to the individual rehabilitation contracts.

2.4 Design Considerations

As with any construction project, the success of a CIPP or FFP installation depends upon the cooperation of all parties, in particular, the owner, engineer, contractor, and manufacturer/supplier. Each party has certain responsibilities that must be accepted if the project is to be completed to the owner's satisfaction. It is the engineer's responsibility to design and specify a rehabilitation system that meets the owner's criteria, is constructible, and is within the capabilities of the available products. While the primary components are generally standard, each installation must be custom designed for specific conditions. All too frequently, the engineer leaves the responsibility of sewer design to the contractor or manufacturer. This has occurred because of the rapid evolution of rehabilitation technologies and the limited availability of design tools for the engineer. This section is intended to provide the engineer with some of the general information needed to design an economical, constructible, and durable sewer rehabilitation system.

The primary design criteria for liner system design are corrosion resistance, structural integrity, and hydraulic capacity. These criteria and other considerations in the design and installation of liner systems are described in the following sections. The responsibilities of the engineer, contractor, and manufacturer are identified.

2.4.1 Corrosion resistance

Corrosion is a problem that should be analyzed by the designer, especially when application in special situations is required. In the initial stage of design, the intended use of the liner should be analyzed to determine the material that is best suited for the expected environment. The proposed lining system should be investigated to conclude whether adequate corrosion testing has been performed by the manufacturer or preferably by an independent party. The tests should accurately model the expected environment in which the liner is to operate.

ASTM F 1216 (1994), "Minimum Chemical Resistance Requirements for Domestic Sanitary Sewer Applications," provides a list of chemicals with which the long-term corrosion resistance of a liner can be assessed. Other chemicals may need to be assessed, depending upon the expected conditions. Although liners have proven to be very resilient to elements which may have caused problems to the host pipe, it is important that proof of a liner's performance with respect to the specific environment in question be provided before acceptance and installation of the product. For uses that involve exposure to unusual chemicals (not standard domestic sewage), the liner must be designed to resist the anticipated corrosive chemicals and pass the corrosion testing performed on the product. If prior testing does not adequately model those conditions that are expected to be encountered, further testing either should be required from the manufacturer or should be performed by the customer before purchasing the product in question. For these situations, the design engineer must use judgment to establish the pass-fail criteria for a nonstandard test.

Lining materials typically employed in the CIPP and FFP have adequate corrosion resistance in sewer line applications. In the CIPP, isophthalic unsaturated polyesters are the major resins to provide the necessary chemical resistance for long service in the sewer environment. Polyesters are created by a reaction between isophthalic/terathalic acid, maleic anhydride, and a glycol. The resin is compounded with a reactive styrene monomer and initiators/promoters to produce cross-linked copolymer matrices. It is not recommended to use less expensive resins such as orthophthalics and terephthalics.

Vinyl ester is created by a reaction of epoxy resins with methacylic acid. Vinyl esters and epoxy resins provide more corrosion resistance, but they are more expensive than the isophthalic unsaturated polyesters. The engineer should evaluate the need for vinyl ester or epoxy resins in the more corrosive environments. For FFP, both PVC and HDPE have excellent corrosion resistance for normal sewage applications.

The possibility of the corrosion process being enhanced by stress in the liner due to service loads should also be evaluated, particularly when a fiberglass-felt composite tube is used. Specifications for determining the resistance of pipe liners to chemicals while in a deflected shape are provided in ASTM D 3681 (1989), "Chemical Resistance of Reinforced Thermosetting Resin Pipe in a Deflected Condition." A strain-corrosion test should be performed on the proposed pipe liner, as outlined in the specification, with chemicals that accurately model the corrosive nature of the expected environment. The strain-corrosion characteristics of the product should be determined either by the manufacturer or by an independent organization. The manufacturer should be expected to provide the results before the designer considers the product for a rehabilitation project. The results from the strain-corrosion test will equip the designer with an improved understanding of the material's corrosion resistance under operating loads over time.

The chemical corrosion resistance of the resin system should be tested by the resin manufacturer in accordance with ASTM standards. The initial physical properties of the specimens should not be significantly reduced (typically limited to 20 percent) when exposed to the given chemical solution for at least 1 year. When exposed to grit which is transported by a flowing liquid, the liner may degrade. A loss of thickness due to the simultaneous actions of abrasion and corrosion can be rapid and may lead to a reduction in the service life. Materials that are more resistant to abrasives may need to be specified, or additional wall thickness may be required.

2.4.2 Structural integrity

2.4.2.1 Structural loading conditions

When performing pipeline rehabilitation using the FFP or CIPP processes, the degree of degradation of the original pipe generally governs the load that the liner is expected to maintain. The two types of structural design conditions typically considered are *partially deteriorated* and *fully deteriorated*.

2.4.2.1.1 *Partially deteriorated condition.* In the case of a partially deteriorated pipe, the pipe may have longitudinal cracks, some cross-sectional distortion, and displaced joints. In a partially deteriorated condition, the pipe is considered to be structurally sound at the time of rehabilitation and is expected to remain sound throughout the design life of the rehabilitated pipe. In this case, the original pipe should be able to continue to support soil loads and live loads. Also, the soil adjacent to the pipe should be able to continue to provide adequate lateral support to the original

pipe. The installed pipe liner will be expected to maintain the external hydrostatic pressure resulting from water that permeates through cracks in the deteriorated host pipe. Additionally, if a vacuum is formed in the pipe, the resulting pressure should be considered as an external pressure for the liner to withstand. A proper analysis should be performed to determine the required parameters of the liner which will adequately handle the external pressure without collapsing.

Standard pipe design equations for circular CIPP and FFP account for distortion, or ovality of the host pipe. Normally, the maximum distortion which is typically allowed in a pipe designed as partially deteriorated is 10 percent of the diameter. The ovality in the host pipe associated with this distortion can lead to a reduction in the structural resistance of the lined pipe. The traditional buckling formula for liners subjected to hydrostatic pressure is based on the classical Timoshenko buckling formula for unconstrained circular tubes. This formula has been modified in Appendix X1 of ASTM F 1216 (1994) (p 2-10), "Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube," by factors which account for the restraint provided by the host pipe and ovality. This equation conservatively predicts CIPP and FFP buckling with ovality of the host pipe of up to 10 percent. Where the host pipe is more than 10 percent out-of-round, special design considerations are required.

2.4.2.1.2 *Fully deteriorated condition.* In the case of a fully deteriorated pipe, the existing pipe is not considered to be capable of supporting the soil and live loads, or may be expected to reach this state during the design life of the rehabilitated pipe. This is evident where sections of the pipe are missing, the pipe has lost its original shape, or the pipe is severely corroded. In this case, the installed liner is assumed to support all loads (i.e., external hydrostatic pressure, soil loads, live loads, and internal vacuum) through interaction with the surrounding soil.

The generally accepted method of analysis of buried pipe is the standard flexible pipe design approach. In this case, the pipe liner is acting solely as the flexible pipe being analyzed. Because adequate lateral support from the soil is essential for the flexible pipe design, it may be advisable to conduct investigations of the soil adjacent to the pipe for sizeable, large-diameter projects. Proper design of the fully deteriorated condition should account for the buckling resistance, bending stresses due to ovalization, pipe stiffness, and deflections. ASTM F 1216 (1994) describes the necessary calculations to be performed for gravity sewers in fully deteriorated conditions.

Sometimes, there are tendencies for design engineers to be very conservative and design all sewers for the fully deteriorated condition. While this might be plausible, particularly when considering the additional longevity of the installed system, over-conservatism leads to designs which are more costly, thereby reducing resources needed to rehabilitate other parts of the sewer system. The engineer should consider these issues in the design process, factoring into the decision process the needs and desires of the local community. In the United Kingdom, the design of trenchless sewers has historically been based on the partially deteriorated condition. It is assumed that the existing hole in the ground already supports the existing loads, and if further erosion can be inhibited through relining, then the hole should continue to serve its original purpose for the life of the liner. While designers in the United States have not generally accepted this approach, it is notable in that it demonstrates a range of design philosophies that currently exist.

The focus of this report is on the design of gravity sewers. However, both gravity pipes and pressure pipes may be rehabilitated using the FFP or CIPP processes, and both should be investigated to determine the extent of deterioration (partial or full) so that adequate design procedures may be followed. When a pipe liner is designed for pressure pipe, it is critical that the

appropriate internal pressure be used. The design pressure should consider the regular system pressure, potential surge pressures, and test pressures. Surge pressure or water hammer, for example, is an extreme change in pressure that can result in loads on the liner which are greater than the expected normal operation loads. Thus, the pipe liner must be able to withstand the maximum surge pressure that is projected to occur. Note, in a partially deteriorated pipe, the original pipe is required to maintain all pressure changes.

2.4.2.2 Long-term strength and stability

The long-term strength and stability of plastic pipe is most noticeably affected by a phenomenon known as creep. When the material creeps, the pipe exhibits a reduction in buckling resistance over time. Creep is a deformation of the material, over time, under constant stress or load. A change in the shape of the flexible pipe may be observed over time due to the external loads. Thus, the buckling resistance of the pipe decreases as a change in the material occurs. Historically, the deterioration of buckling resistance, over time, has been handled through the implementation of an adjusted value of the flexural modulus of elasticity.

Research has been performed under the CPAR Program by WES and TTC to develop relationships that accurately model the expected buckling resistance of the pipe liners over time. The overall objective of this research was to evaluate the long-term structural behavior of CIPP and FFP liner products made by different manufacturers. A test program was designed to simulate the sustained hydrostatic loading that would be experienced by liners constrained in partially deteriorated gravity sewer pipes. The results are published in CPAR task report, "Long-Term Structural Behavior of Pipeline Rehabilitation Systems" (Guice et al. 1994).

Approximately 200 tests of seven different products made by five manufacturers were conducted. The evaluated products included liners made from thermosetting polyester and vinyl ester resins and thermoplastic PVC, with dimension ratios (diameter to thickness) ranging from approximately 31 to 61. Each of the products differed in construction (e.g., number and types of material layers), installation (e.g., inversion and winching), and curing process (e.g., steam and hot water). The 10,000-hr tests of 6-ft-long, 12-in.-diameter encased plastic liners subjected to external hydrostatic pressure provided data on the long-term buckling characteristics of the different products evaluated.

Test results indicate that the creep behavior of the plastics leads to buckling of the liners under significantly lower pressures as the load is sustained over longer periods of time. With the use of regression analyses extrapolated beyond the 10,000-hr test period, the buckling resistance of the liners may be estimated. The current practice, as related to the Design Considerations in ASTM F 1216 (1993), for analysis is shown to estimate long-term buckling pressures, generally less than the extrapolated experimental data for most of the evaluated products. Assuming that appropriate values of the modulus of elasticity, creep-reduction factor, and restraint factor are chosen, the current practice can be viewed as being conservative for the products evaluated under conditions imposed in this test program.

Because the values chosen can have a very significant impact on the design of FFP and CIPP liners, the designer should be careful to employ both reduction and enhancement factors that accurately model the present and projected strength of the rehabilitation system. The factors should not be determined independently of each other and should not be based on arbitrary considerations, but on reliable test results. Short-term material tests alone cannot accurately reflect the long-term

behavior of CIPP and FFP tests. The CPAR task report (Guice et al. 1994) and related references should be reviewed for further information and guidance in accurate factor selection. As a result of the research conducted for this study, a design approach based on a constrained ring model is being developed. Reports on this research will be published by the Corps of Engineers and the TTC at a later date.

2.4.3 Hydraulic capacity

Because changes to the pipe flow characteristics are imminent due to rehabilitation, an evaluation of the impact on the overall system should be performed. Of the many factors affecting the hydraulic flow in a pipe, pipeline rehabilitation systems usually change the flow cross-sectional area, internal pipe roughness, and the pipe shape. The change in pipe size typically reduces the flow cross-sectional area and hydraulic radius components of pipe flow calculations. The flow cross-sectional area reduction can be substantial where circular pipe sections are rehabilitated using a slip-liner system, due to the annulus formed between the host pipe and the liner.

Calculated hydraulic capacities can be determined through the traditional Manning's equation. Estimates of the Manning's coefficient for the CIPP should be based on documented test results of in-service installations since the CIPP process leads to variable roughnesses, depending on the condition of the host pipe. The flow capacity of the CIPP liner should be based on the inside diameter (ID) of the host pipe reduced by twice the wall thickness of the liner.

Although these reductions in flow exist, pipe capacity can often be maintained due to the reduction in I/I and inflow entering the system and reduction in the roughness of the host pipe. The total impact of the rehabilitation system on flow capacity, both pros and cons, should be closely scrutinized.

Because any rehabilitation will affect the performance of the other parts of the system, the system-wide implication of the project should also be evaluated. Renovation can impact the hydraulic performance by increasing or decreasing the flow through the pipe. Possibly, the result could be flooding downstream and, in some cases, increased pollution caused by spills from storm sewage overflows. Incidentally, these problems may not be local to the rehabilitated pipe; improvements in one area may result in more frequent surcharge in structurally degraded pipes, causing additional failures and problems in other areas. All of these factors should be investigated before a pipe-lining system is designed. For further guidance and information on design considerations, the manual entitled *Existing sewer evaluation and rehabilitation* (ASCE 1994) compiled by the ASCE Existing sewer evaluation and rehabilitation Task Force should be consulted.

2.4.4 Service lateral and manhole tie-ins

The design of a liner system may prove to be inadequate to the owner if proper consideration is not given to the details at service lateral and manhole tie-ins. All tie-ins should be free of obstruction once the pipe liner is installed, and the openings should be restored to approximately the original size. Remote-control cutting methods and CCTV can be used to open the rehabilitated pipe to service laterals; however, excavation and tapped connections may be required. The contractor should be responsible for identifying and confirming all locations of lateral tie-ins within a lined section before and after installing the liner. The owner must make the decision on whether or not a lateral tie-in should be reinstated if the lateral is not in service. While dimpling of the CIPP liner will generally occur at the laterals, it is possible for laterals to be missed for

reinstatement if accurate records are not maintained. Dimpling is not always apparent for FFP liners, but rounding devices tend to enhance the dimpling effect.

If designed to reduce inflow and infiltration, the liner should be adequately sealed at laterals to ensure that there is no inflow into the pipe. This can be achieved by adequately grouting around the openings or by using sealing gaskets. Grouting may not be needed with CIPP, but it may be needed with FFP. Either chemical or cementitious grout may be used, but the decision is generally subject to the degraded state of the pipe at the junction. When large voids are present, cementitious grout can be used as a rigid filler to recreate the original pipe.

In situations where there are protruding or recessed lateral connections, robotic techniques may be prescribed to remove the protrusions. Significant advancements have occurred recently in robotic technologies for sewer system rehabilitation, and such techniques should be considered in preparing surfaces for lining and in joining the laterals and lined host pipe for tight connections. Systems to rehabilitate and tie lateral lines into the main line or the main line with a water-tight seal are being used in some parts of the country, and the use of these systems is expected to grow considerably.

The flared ends of the liners at the manhole should be sealed tightly to the host conduit and manhole walls. The seal should be made with a resin mixture that is compatible with the liner. Other end seal systems or press seal gaskets may be acceptable.

Occasionally, some laterals are inadvertently omitted from reinstatement, and backups occur in residences. This contingency should be anticipated, and the communication channels necessary to get quick action should be set up among the customers, owner, and contractor. It should be the responsibility of the contractor to ensure that all laterals are opened before services are restored.

2.4.5 Design practices/design for field conditions

2.4.5.1 Safety factors

The designer should carefully consider all facts that may have an impact on the design of the pipe liner. Appropriate decisions should be made during the design calculations to accurately incorporate the installation/field unknowns. Research performed to develop the relationships used for designing rehabilitation systems is generally under ideal conditions, so the basic parameters can be isolated by the investigators. Field installations of the products are typically not under ideal conditions; therefore, designers must impose factors of safety which account for uncertainties that exist in the field. Currently, factors of safety for the buckling resistance of liners range between 1.5 and 2.5, depending on the confidence the designer has on the conditions imposed. Once further research is conducted and as more field installations are made under other conditions, designers will have more confidence in the choice of factors of safety. As the understanding of material behavior is increased, the safety factors can be reduced, resulting in less conservative and more cost-effective designs. Safety factors are also highly dependent upon the quality of the product and installation, which are directly affected by the attention to design details and construction workmanship.

Before any design procedure is applied, the methodology (e.g., theory, applicability, special conditions, etc.) should be thoroughly reviewed and understood so that a correct application of the procedure is used. Safety factors are not intended to make up for deficiencies in the understanding of the principles of design.

Bonding between the host pipe wall and the liner is generally not considered since it may be difficult to achieve uniform bonding in wet or deteriorated conditions. However, CIPP products that allow resin migration from the backside of the liner into the host pipe during cure provide for some degree of mechanical locking to the host pipe. This locking provides additional safety factors which are not considered in design. Theoretically, chemical bonding of the CIPP to the host pipe could be achieved with specific resin systems and metallic host pipe materials that are cleaned to the white metal prior to liner placement. However, achieving these conditions in a sewer environment is highly unlikely. Bonding is not achievable with FFP and should not be considered in the analysis.

2.4.5.2 Materials

The resin-absorbing fabric tube is an important component of the CIPP. The fabric is primarily used to facilitate installation of the resin system inside the host pipe. Unless it is reinforced with glass, carbon, or other fibers, the tube does not contribute significantly to the final structural properties. It is important that the composition of the tube be compatible with the specified resin system and that de-bonding, delamination, or other forms of degradation not occur due to incompatibility of materials. This may be a consideration in systems which use an encased elastomeric layer within the wall thickness. ASTM F 1216 (1993) provides guidance on testing for delamination. The engineer may request that physical characteristics and properties of the tube be submitted prior to acceptance.

Prior to curing, the fabric tube is quite flexible and is subjected to stretching and other pressures during installation. Allowances should be made for the stretching of the tube circumferentially and longitudinally. The tube will stretch to fit the shape of the host pipe. This should be fully considered, or it could result in a net reduction in the installed wall thickness. It is generally recommended that the stretching of the tube should be limited to 5 percent of the original dimensions.

Stretching can be controlled by the installation pressures. The manufacturer should provide a range of pressures that would be sufficient to hold the liner against the host pipe while not causing excessive stretching or other damage. After installation has been initiated, the pressures should be maintained in the specified range. If installation pressures deviate from the specified range, the finished CIPP or FFP product should be carefully inspected for remediation.

The contractor must also make allowances for stretching and should provide a minimum length of resin-impregnated tube that can fully span the actual distance between manholes.

Payment is typically based on actual field measurements between the centerlines of manholes, not on the actual length of liner delivered to the site. The contractor should be responsible for verifying the lengths and diameters in the field before fabricating the tube.

Tolerances on the installed liner thickness should be specified by the engineer. It might be desirable to allow for up to 5 percent reduction in the actual measurements to account for normal

variations of field installations. ASTM D 2122 (1994), "Determining Dimensions of Thermoplastic Pipe and Fittings," provides guidance in wall-thickness measurements. Such measurements may be made by an independent laboratory. If hydraulic flow is a primary consideration, then the wall-thickness variation may be limited to no more than 10 percent of the design thickness. It should be noted that this may be overly restrictive for some liner systems which provide calibration or heat-containment tubes.

Resins and tubes may come in different colors. The wall color of the interior pipe surface of the liners after installation should be white or light-colored and nonreflective to facilitate a detailed examination with CCTV.

Some companies inspect the tubes under ultraviolet light to detect pinholes in the thin elastomeric coatings. Any pinholes detected are sealed at the plant. Lack of attention to this detail could cause a loss of resin in the vicinity of the pinhole during installation. The manufacturer should exercise care during transportation, handling, storing, and installation to ensure that the material is not damaged.

2.4.5.3 Resin impregnation

A critical aspect of ensuring the installed product's overall performance is that there be complete and uniform distribution of resin throughout the fabric tube. To ensure proper saturation of resin, the liner should be vacuum-impregnated (wet-out) with a volume of resin sufficient to fill all voids in the tube for the given thickness and diameter. Adjustments should be made to account for the migration of resin into joints, and cracks and for the volume changes due to polymerization. If plastic coatings are used, it should be specified that the coatings be translucent to allow in situ inspection of the installed liner for verification of resin-impregnation. At least a 24-hr notice should be given to the engineer on the wet-out process. The engineer may desire to inspect the wet-out process for verification of the materials and procedures being used.

For some situations, it may not be practical or possible to do the vacuum-impregnation at the manufacturer's plant. This is particularly true when large diameters and lengths are used. In these cases, most manufacturers have the ability to do remote impregnation with transportable equipment.

2.4.5.4 Curing

For proper curing, close control on the heat source, the rate of heating, the distribution of temperatures, and the heating durations is required. The specific requirements for different resin/catalyst systems are available from the resin manufacturers: these may be requested by the engineer. However, the engineer must work closely with the manufacturer or contractor to select a curing schedule that fits the particular site conditions.

Some of the factors that could lead to improper curing of the resin include: ruptures in the tube, equipment malfunctions, or lack of attention given to temperature monitoring instruments. Ruptures in the tube are possible if the tube is snagged, punctured, or over-stressed during installation.

Monitors are generally available at the heat source to measure the incoming and outgoing water/steam supply. Thermocouples should be attached near the beginning and end of each installation to measure the temperatures and verify that exothermic reactions have occurred. Complete logs of the temperatures should be requested by the engineer.

An adequate supply of water for heating, recirculation, and curing should be the responsibility of the contractor. Permits may be required for approval to use a municipal fire hydrant. If access to a fire hydrant is not available, a private tanker truck or other sources of water supply will be required.

The cooling-down process is also important to observe. Sufficient attention should be given during the release of the static head so that a vacuum will not be developed that could damage the installed pipe.

2.4.6 Installation practices

All installation operations should be carefully considered and planned to ensure a smooth, problem-free installation. Necessary site preparation should be completed prior to initiation of the installation process. Because installation, preparation, and equipment procurement may greatly impact the cost of installing one product as opposed to another, it may be desirable to investigate the installation set-up requirements of each manufacturer prior to the selection of a rehabilitation system.

As is common to all construction projects, rehabilitation systems are affected by external factors that should be carefully considered for the project to be a success. Although most manufacturers have considered these problems in the design and installation of their product, the construction-related issues should be considered before selection of a particular technique. The main construction issues to be considered include: safety, preparation, methods of working, and onsite supervision. Most importantly, the engineer and contractor should be familiar with the installation process to be performed and cognizant of any problems that have occurred in past installations due to inadequate site preparation.

It is very important that the installation crew be well-trained and experienced in the techniques employed. Many of the problems encountered in a rehabilitation project are due to poor workmanship, especially in the CIPP where the liner material is wetted out by resins that must be kept chilled until installed. The experience of the crew will ensure that the liner is installed before the resin initiates curing or becomes stiff and unusable prior to installation especially in hot weather.

2.4.6.1 Pre-installation preparations

Specifications for the preparation (e.g., cleaning and inspection) of the line and bypassing of flow around the line are provided in section 7 of ASTM F 1216 (1994). Some of the critical steps in preparing the line for installation are described in the following paragraphs.

The contractor should evaluate the atmosphere for the presence of toxic or flammable vapors or a lack of oxygen. The contractor must follow local, State and Federal safety regulations, with particular attention to those issues dealing with work on elevated platforms, entry into confined spaces, and handling/disposal of hazardous materials. Material safety data sheets (MSDS) should be obtained from the manufacturers of all hazardous materials.

The contractor and engineer should review recent CCTV inspection tapes and reports. Point repairs must be satisfactorily completed. This should include the handling of any obstructions which may impact installation of the liner, restrict hydraulic flow, or limit the ability to conduct postinstallation inspections. Common obstructions include protruding service taps, collapsed or crushed pipe, excessive reductions in the cross-sectional area, dropped joints, heavy solids, tree roots, and intersecting services.

Internal debris should be removed immediately before installation using high-velocity jet cleaners or other hydraulic or mechanical equipment. NASSCO provides recommended specifications for collection system cleaning. The contractor should mobilize equipment, material, and personnel and inform the engineer of the work schedule. This should provide the engineer with information needed to avoid conflicts with other aspects of the construction to allow for inspection and testing and to notify the public. A final pre-installation CCTV inspection of the pipe immediately before liner insertion should be the responsibility of the contractor. These tapes should be made available to the engineer. If bypassing of the flow is required, it should be analyzed so the service to consumers is minimally disrupted or compromised. This requires an analysis of the capacity needed to handle the flow.

2.4.6.2 Field samples for material testing

The engineer should expect the contractor or manufacturer to provide certified copies of all test reports on the properties of the selected resins. It may be desirable to require the submission of some number of test results from previous field installations of the same resin system and tube materials to verify the physical properties in prior field applications.

It is very important that field samples be collected, rather than laboratory samples, in evaluating the properties of the installed liner. Field installation and curing conditions can lead to properties of the installed liner that are significantly different from design or laboratory conditions. Samples collected from intermediate points in a liner installation (e.g., manholes) are the most appropriate for assuring the quality of the installation. The sampling frequency may vary, but a minimum of six tests per installation should be expected (three specimens from two samples). Samples may also be used for verification of the installed thickness and other properties. It is desirable to request that the remaining liner test samples be labeled and made available to the owner or engineer for random testing.

ASTM F 1216 (1994) specifies methods that should be used in gathering field samples of the liner and requirements for adequately testing the material being installed. Further guidance is provided in the CPAR task report, "Long-Term Structural Behavior of Pipeline Rehabilitation Systems " (Guice et al. 1994). The report cites several issues which play significant roles in the collection of field samples and compilation of test results. The first issue is the type of tests to be used in evaluating the modulus of elasticity of the liner. Compression tests can be used, but are generally more difficult to conduct for liner samples, and the test results typically have less reliability. The current practice is to use the flexural test because it is easier to perform and is

more appropriate in application than a tensile test. The ring compression test (ASTM D 2412 1994) does not yield a modulus that is applicable in the buckling analysis of constrained liners in partially deteriorated sewers.

A related issue is the actual preparation of the specimens. Specimens may be taken from the whole cross section and tested, or they may be machined or modified in some way (e.g., removal of film coatings) prior to testing. While machined or modified specimens may be adequate from the quality assurance standpoint, they do not necessarily provide the type of modulus needed for design or analysis because the actual liner cross section may not be homogeneous. The most desirable specimen is the one that will best model the characteristics of the installed liner.

Several issues that can affect the apparent elastic modulus for a liner product have been identified. It is important that such issues be given appropriate consideration, particularly when comparing products or when considering appropriate values to be used in the design process.

2.4.6.3 Postinstallation

In addition to verification of material properties, there are other activities that should take place after installation. First, the contractor should perform postinstallation inspection of the installed liner. Tapes of the CCTV inspection should be requested by the engineer. Voice descriptions on the tape should include the location of each lateral, deficiencies of joints at lateral connections, deficiencies of joints in the mainline, and other discernible features. The contractor should also clean up areas disturbed by these operations and restore them to a condition at least equal to that which existed prior to the start of the work.

2.4.7 Technical envelope

The applicability of the lining system for the geometry of the piping system is an issue that should also be explored. Although research has been performed on pipe liners and their performance in various situations, the specimens used in the tests are generally in the mid to lower range of possible diameters (10 to 18 in.). Depending on the type and manufacturer of the pipe liner chosen for the job, the possible diameters can range from 4 to 108 in. When designing for large-diameter pipe rehabilitation task, a discrepancy between the expected performance and the actual performance may occur. This stems from the lack of data on the performance of pipe liners when used for large-diameter pipe rehabilitation projects. At this point, it is difficult to project how, or if, the design procedure for rehabilitation jobs on large-diameter pipes should be altered (e.g., safety factors); therefore, the designer should be aware of the possibility of discrepancies and should consult the manufacturer for information on the past performance of the pipe liner when used for large-diameter versus small-diameter rehabilitations. Also, if feasible, the designer should consult past customers/designers who may have used a similar product for large-diameter rehabilitation and gain additional knowledge from their experience.

Elbows and bends in pipelines can be successfully lined with some CIPP products, but they present special circumstances both during installation and service. Wrinkling of the CIPP may occur on the inside of the bends, but typically causes no significant detrimental structural or flow-capacity effects. The liner will stretch to fit the outside of the bend during installation and should be inspected for a tight fit. The manufacturer should be consulted for information on any special preparation that may be necessary at the pipe bend before installation.

If the cross section of the host conduit has flat sections or is of noncircular shape, the liner will not be able to sustain as much load as if it were circular. Therefore, special considerations must be given during design.

2.4.8 Public relations

Keeping the public notified of the activities associated with rehabilitation of their sewers is very important. Many times it turns out to be a critical measure of the success of the project. Notification of the public is normally the responsibility of the engineer.

Because CIPP and FFP typically have minimal surface disruptions and take only a few hours to complete, some residents may never be aware that the construction has taken place. If the taxpayers are made aware of such nondisruptive improvements to their sewers, then it improves the ability of the municipal authorities to secure more regular maintenance of the sewer system. Failure to reopen a lateral and slow response to such a failure engender poor public relations. It is essential that all affected parties be notified in advance when their service laterals will be out of commission. They should be advised against using water until services have been re-established. The public should also be informed of odors resulting from the curing of resins which may be noticed during and shortly after the installation. Noises associated with installation equipment and traffic disruptions are minimal, but should be anticipated by the engineer, and the public should be notified. Also, if installations occur at night, the public should be made aware of the lighting required for such operations.

2.5 Bid Documents

2.5.1 General

The bid documents prepared by the owner/engineer provide the contractor with vital information required for bids as well as other requirements of the particular CIPP or FFP rehabilitation project. Bid documents prepared for a job utilizing CIPP or FFP technology may include all of the items required in a typical pipeline project such as Invitation for Bids, Bill of Quantities, Specifications, Plans, Bonds, etc. Because of the nature of these sewer rehabilitation processes, portions of the bid documents will have unique requirements, as discussed in the following subsections of this chapter.

Note that this discussion of bid documents is based upon recommendations for average size projects. Projects of smaller or larger scope may require more or less with regard to bid document items than are presented. Some of the discussions in this section have been elaborated upon in previous sections of this chapter, but are summarized here for completeness.

2.5.2 Deliverables (scope of work, plans, and specifications)

Potential bidders on a job utilizing the CIPP or FFP process should be sent a copy of the plans and specifications for the job, along with documentation defining the scope of work. This information is vital to the contractor in formulating an accurate competitive bid and in preventing potential problems.

2.5.2.1 Scope of work

The scope of work for a job using a CIPP or FFP process should inform bidders of the work required in the contract to complete the project. This work may include, but not necessarily be limited to, the following tasks:

a. Sewer line cleaning.

b. Sewer flow control.

c. Sewer pipe lining.

d. Television inspection, main and lateral sewers before lining (if it is not done during the SSES, or if the SSES needs to be updated.)

e. Television inspection, main and lateral sewers after lining.

f. Lateral reinstatement.

g. Traffic maintenance.

2.5.2.2 Plans

As with most sewer rehabilitation jobs, plans should include the location of the pipe section of interest, location of all manholes and other appurtenances, joint locations, pipe diameters, and locations of utilities that might be sources of inflow. In addition, nominal inside diameters of pipes and tolerances present in the section should be indicated since this is the main parameter used in pipe liner design.

2.5.2.3 Specifications

Specifications should target performance requirements and should address minimum requirements for materials, chemical and corrosion resistance, preparatory procedures, installation considerations, testing, and safety.

2.5.2.3.1 *Materials*. The owner or owner's representative should specify allowable liner material alternatives. Materials used in the CIPP process include flexible fiber fabric and either polyester resin, epoxy resin, or vinyl ester resin. With the FFP process, PVC or high-density polyethylene is typically used. The tube to be used as a liner should be specified to fit neatly into the existing pipe with an allowance for circumferential stretching during inversion and should be capable of withstanding installation pressures and temperatures.

2.5.2.3.2 *Preparatory procedures*. Preparatory procedures typically include cleaning, inspection, obstruction removal, and flow control. Specifications should require the removal of all debris from the sewer line. The removal of obstructions such as solids, dropped joints, and roots identified during initial inspection should be specified. Specifications covering preparatory procedures should ddress the diversion of flow during construction. Important considerations for the diversion of flow

include the diversion procedure, bypass flow discharge points, required capacity of bypass lines and pumps, and termination of homeowner services. Other preparatory procedures typically specified include service connections and access points.

2.5.2.3.3 *Installation considerations*. Typically the contractor will decide which liner installation procedure will be used on the job. The owner, however, should specify any general installation guidelines that are necessary to ensure a quality project. In addition, specifications should require the contractor to adhere to all regulations that govern the installation procedure.

2.5.2.3.4 *Safety*. Specifications should address safety concerns inherent in the handling and installation of CIPP and FFP products. Laws, ordinances, and regulations that include environmental, occupational, and consumer concerns must be followed. People handling and assembling the flexible resin-impregnated tube used with the CIPP process should be informed of the hazards to human exposure of the resins and other chemical additives incorporated in the tube. These hazards are usually stated in the MSDS of the manufacturer.

Vinyl ester and polyester resins contain styrene which has been listed in the MSDS and should be handled and treated according to the MSDS instructions. In addition, the resins and their vapors are flammable, and many types of resins are not approved by the NSF for use in potable water systems. Some of the U.S. Government laws and agencies with regulations governing the handling of these resins include:

a. U.S. Food, Drug, and Cosmetic Act.

b. U.S. Food and Drug Administration.

c. Occupational Safety and Health Act.

d. Federal Department of Transportation.

e. U.S. Department of Agriculture.

Safety regulations concerning the use of steam and working in confined spaces and on elevated platforms should be observed. The manufacturer is a good source of information regarding safety concerns and regulations.

2.5.2.4 Sewer system evaluation and survey report

In addition to the plans and specifications, the owner should include in the bid documents a copy of the SSES including interpretation and flow rates of any sewers to be bypassed. The SSES will aid the contractor in assessing the job and formulating a bid. The SSES identifies areas in the existing sewer line which are sources of I/I, attempts to quantify the I/I in these problem lines, recommends a rehabilitation plan, and gives the maximum flow rates in these lines.

The SSES includes a videotape and log documenting the interior condition of the pipe. If the videotapes in the SSES report were shot long before the actual lining, or if some of the governing factors have changed since shooting these tapes, it should be updated before the job execution. This documentation can be useful to the contractor in bidding, planning, and installing the liner and also serves as means for comparison after the job has been completed. The flow rates of the

existing sewer lines are also important to the contractor since he must use these values in designing any bypass lines for diverting the flow during construction.

2.5.3 Minimum performance requirements and performance period

To ensure that the pipe liner performs adequately, minimum performance requirements should be presented to the contractor via the contract documents. The criteria typically used in gauging performance include inflow/outflow, material properties, and structural performance.

2.5.3.1 Infiltration/exfiltration

Typically infiltration and exfiltration of groundwater or other leakage into or out of the sewer liner should not exceed 50 gal per mile of sewer per inch of inside diameter of the sewer per 24 hr. In no case should it exceed 2,500 gal per mile per 24 hr. Various tests are currently used to measure inflow/outflow (refer to Section 5.8), and the desired test should be specified.

2.5.3.2 Material properties

Physical properties of the material such as flexural strength, modulus of elasticity, compressive strength, and tensile strength should be specified according to the values used in determining the pipe wall thickness. The chemical resistance of the material should also meet ASTM F 1216 (1994) standards for CIPP, ASTM D 3034 (1994) for PVC FFP, and ASTM D 3350 (1994) for HDPE FFP.

2.5.3.3 Structural performance

If the host pipe is deteriorated or partially deteriorated and expected to be severely deteriorated during the future life of the liner, the lining pipe should be capable of withstanding loads from earth pressure, live loads, and hydrostatic pressure from groundwater. Therefore, the owner should specify the lining characteristics based on the status of the host pipe and inform the contractor to meet these requirements.

2.5.4 Minimum qualifications

To ensure a safe, efficient, quality project, the owner should present to the potential contractors a list of minimum qualifications required for the job. These minimum qualifications typically include a minimum number of references where the specified product was used under similar conditions, financial data on the contractor, product manufacturer, and any subcontractors used. The deadline for submittal of these qualifications from the contractor to the owner for verification should be specified as well. This deadline should be prior to the contract award and is typically the same time as the bid submittal.

It should be noted that there are trade-offs made by the owner when selecting restrictive qualifications of the contractor. It reduces risks to the owner; however, it could potentially increase costs by reducing the number of potentially qualified bidders and by limiting competition. The balance of risks and costs may vary from one situation to the other, and the owner should consider each situation independently.

2.5.5 Minimum submittal requirements from contractor to owner

Submittals from the contractor to the owner typically include details on construction methods, project scheduling, qualifications, certifications, quality control, construction records, and safety. The timing of the various submittals should be in accordance with the submittal schedule laid out in the contract. Section 2.6 covers, in detail, all the needed submittals from the contractor to the owner.

2.5.6 Requirements for protecting existing structures and site features

When necessary, the owner should specify the level of noise, lighting, traffic interruption, etc., which will be acceptable during construction. In addition, if the contractor has to disturb the surrounding environment or existing utilities/structures, he should be required to restore them to their original condition.

2.5.7 Inspection requirements and action levels

Inspections are essential to ensure adherence to contract specifications and required quality of the finished work. Inspection requirements are typically presented as part of the specifications. With CIPP or FFP jobs, an initial inspection should be performed by the owner or his representative to establish the preliminary condition of the existing pipe. After the bid has been awarded, several inspections are typically required by the owner throughout the job duration. The party responsible for payment and performance of these inspections should be clearly specified by the owner. Typical inspections required during construction include, but are not limited to:

a. Pre-inspection of the materials to be used in the lining process (liner, resin, etc.).

b. Inspection of the host pipe to ensure adequate preparatory cleaning.

c. Spot inspections during liner installation to ensure accepted installation procedures are followed.

d. Final inspection of the lined system before acceptance.

2.5.7.1 Pre-inspection of materials

The owner should inform the contractor of material pre-inspection requirements. Contractors should be required to furnish a sample from the manufacturer for testing by a third party. The sample should be representative of the liner material to be used on the job. Material properties of the sample are typically tested to ensure adherence to specifications and manufacturer claims.

2.5.7.2 Preparatory cleaning inspection

Just prior to the liner installation, the host pipe should be inspected to ensure it has been adequately cleaned and prepared. This inspection is typically carried out by either visual inspection, in the case of large-diameter pipes, or by robotics (CCTV).

2.5.7.3 Spot inspections during liner installation

During the liner installation, a representative of the owner should be onsite to ensure accepted installation procedures are followed. Proper installation is especially important with CIPP and FFP, since the ultimate performance of the liner is affected by the installation procedure.

2.5.7.4 Final inspection

Final inspection of the finished liner involves testing for watertightness, adequate material properties, and general suitability to the desired application. Watertightness of the liner is typically gauged under a positive head. The procedure for this testing process, along with minimum acceptable head loss rates, should be addressed in the specifications. Testing of the material properties of FFP and CIPP may include initial flexural strength, modulus of elasticity, and thickness. If the CIPP or FFP process is used, specifications may call for the securing of a CIPP sample from a section of the cured pipe at an intermediate manhole or termination point held in place by a suitable heat sink. A sample should be obtained for each sample length designated in the contract documents or purchase order. Samples of the liner should be approximately 2 ft in length. Both the CIPP and FFP samples should be tested in accordance with ASTM D 790 (1994) with modifications to test the full wall thickness of curved samples. These modifications involve cutting the samples in the axial direction (longitudinal pipe axis) and placing the curved (interior) surface of the specimen in tension while testing. Also, for samples greater than 0.5 in. thick, the width-to-depth ratio of the specimen should be increased to a minimum of 1:1 and should not exceed 4:1. These tests should meet the minimum material properties and thickness established by the engineer and called for in the specifications. Final acceptance is also typically predicated upon a final television inspection in the presence of the owner's representative. This inspection should establish that the liner is free from visual defects, deflections, holes, and rough edges at service connections and that the liner is suitable for the application.

2.5.8 Remedial action requirements

Even the most comprehensive contract will not cover all of the problems that typically occur on a project. Owners, therefore, should attempt to lay down a course of action for the contractor to follow in the event that the job does not go as planned. These remedial action requirements should cover foreseeable problems, and they should be spelled out in the contract. Typical problems that may occur on a CIPP or FFP job include leakage, material properties that do not conform to specifications, non-fully expanded liner, new defects appearing since the last inspection, late performance, and total inadequacy for the required application.

If testing reveals leakage that does not meet the specifications, patching and/or grouting may be required when possible or liquidated damages may be assessed based upon a damage assessment schedule previously established in the contract. Damages based upon a damage assessment schedule should also be assessed for inadequate material properties such as pipe thickness. The damage assessment schedule for material properties may be based upon safety factors. With this approach, material properties recovered from the samples may be inserted in the appropriate design equations, and the safety factor can be computed from these values. Comparison of the computed safety factors with the safety factors in the damage assessment schedule will then yield the appropriate assessment.

It is recommended that each job have onsite supervision with someone with the experience and authority to make decisions with respect to remedial actions in order to minimize delays and disruptions.

2.5.9 Measurement and payment

2.5.9.1 Measurement

Measurements for payments should be made from center to center of manholes or to the inside face of terminating structures. Sewer lining is typically bid on a price per unit length basis for each nominal diameter, and measurements should be consistent with this scheme. Specifications should require remeasurement by both the owner and contractor when a discrepancy in measurement exceeds a specified level such as 10 percent.

There may be differences between the design thickness and the nominal size of the liner due to sacrificial layers. This should be noted when measuring wall thickness. Specifications, measurement, and payment should be based on the design thickness.

2.5.9.2 Payment

Payments for job activities should be based on the unit price bid for the particular activity. The breakdown of activities for bids and payment typically includes sewer line cleaning, television inspection, pumping and bypassing, removal of obstructions, installation of liner, reinstatement of service connections, and final television inspection. Obstructions and lateral reinstatements are typically paid per occurrence rather than price per unit length.

2.5.10 Dispute resolution

Because of the many variables encountered in a typical existing sewer system, many of the potential problems are not foreseeable and may not be covered in the contract. As a result, jobs utilizing these new technologies may be particularly vulnerable to disputes. In order to avoid lengthy and costly court battles when disputes arise, a good dispute resolution plan should be incorporated into the contract and presented to the contractor. The dispute resolution plan should attempt to settle disputes in a timely manner while avoiding legal proceedings. These plans typically require both parties to submit to arbitration by a third party when the parties cannot resolve the dispute on their own. Dispute Review Boards and mediation are additional methods sometimes used in settling disputes. Maintenance of a videotape and suitable log describing the pipeline condition before and after construction will also serve to reduce disputes.

2.6 Submittals from Contractor to Owner

2.6.1 General

Submittals requested by the owner from the contractor are critical to provide the basis for monitoring details of the specific CIPP or FFP process to ensure compliance with the project specifications. These submittals, or portions of it, can be provided at various points during the procurement and construction process including:

a. Prior to tendering or bid opening. Prequalification of the contractor and the lining supplier allows a thorough technical evaluation of the product and contractor without the influence of the contract amount or the bid price.

b. With the bid submittal package.

c. After contract award, but prior to construction.

d. During the construction period.

The submittals of interest include details on construction methods, project scheduling, qualifications, certifications, quality control, construction records, and safety. These items will be outlined in this section. Note that this submittal discussion is based on recommendations for sizeable projects. Projects of smaller scope may require only a portion of the submittals presented. Some of the discussions in this chapter have been elaborated upon in previous sections of this report, but are summarized here for completeness.

2.6.2 Construction methods submittals

The construction methods submittals explain in detail the various steps involved in the construction process. They would include equipment, techniques, materials, and other permanent and temporary features such as treatment at manholes and service laterals or rehabilitation. The submittals should explain the processes of traffic control, flow management and bypass (treatment of service as well as mainline flow), cleaning, solids disposal, inspection (including verification of service lateral and defect locations), pipe preparation, lateral reinstatement, postinspection, reinstating pipe flow and surface restoration. Items specific to CIPP include resin-impregnation, tube inflation, cure, cool down, release of pressure, and finishing ends. For FFP, the specific steps are folded pipe insertion, heating and expansion, cool down, relief of pressure, and finishing ends.

Submittals should also include details on repair procedures for the CIPP or FFP if damaged during installation, procedures for the owner to make future side connections, and procedures for the owner to repair the liner in the future, if it is inadvertently damaged. This may be handled during prequalification.

2.6.3 Sequence of operations and scheduling

The owner should know the sequence of construction corresponding to the various items reported in the Construction Methods submittal. For projects with multiple installations and items of work to be performed by the owner and/or subcontractors, the timing of each installation should be submitted.

2.6.4 Layout of operations

Construction site layout information is important to the owner to verify that the construction area is in fact nondisruptive and that operations do not infringe on personal property or interfere with any public or private operations. A sketch should be submitted (often marked on copies of the project construction plans) indicating storage areas, manhole locations, construction preparation areas, and locations of all equipment.

2.6.5 Safety plan

The safety plan is critical to the construction operation to ensure that the public and workers are protected from construction hazards. This safety plan should include a submittal of the contractor's safety procedures for his workers (addressing, among other things, entering and working in confined spaces) as well as a traffic control plan to ensure public safety. All safety procedures should be in accordance with local and Federal standards.

2.6.6 Construction records

Various submittals are required during the construction process to monitor the project. These include pre-inspection video, inspection log, locations and types of point repairs, materials installed, delays including extent and cause thereof, unusual problems and conditions encountered, post-inspection video (providing documentation of as-built conditions), field samples (including test locations and testing results), and a construction log indicating timing and completion of the various construction steps.

2.6.7 Certifications

Certifications should be provided that the various materials used for the construction project meet the specifications. For CIPP, this would include resin system and tube material. For FFP, submittals on the folded pipe should be prepared. Material safety data sheets should be provided on all hazardous materials in use.

2.6.8 Qualifications

Verifying the qualifications of the contractor to complete the work specified is critical to ensure a quality project. The number of required references should be specified. Submitted references should be contacted by the owner to verify satisfactory performance. References should be on installing the specified product in similar applications. Supporting financial data on the company should also be submitted and reviewed to ensure that the contractor and/or pipe supplier will be available in the long term to support the product. Similar background information should also be supplied on all subcontractors.

2.6.9 Quality control plan

The specifications should clearly address all quality control items related to qualifying materials, construction procedures, and performance testing of the finished product. For CIPP and FFP projects, this would include previous corrosion, physical property, longevity, structural, flow capacity, and infiltration reduction testing of the CIPP or FFP product to ensure that the proposed materials will meet the owner's needs. All test data submitted should be on the materials processed under similar conditions to those when installing the product (e.g., for FFP, data on polyethylene or PVC pipe that has *not* been folded and formed should not be accepted). On some projects, structural design submittals may also be required. Unless design data are supplied by the owner, design submittals must follow pre-inspection of each pipeline. In addition, quality control procedures used in tube manufacture and resin system evaluation should be submitted for CIPP. For FFP, quality control procedures on folded pipe manufacture are applicable. Installation quality control is typically evaluated through field sample testing of physical properties and leakage testing. Leakage is often gauged during cure of CIPP under positive head unless a removable inflation

bladder is used. For FFP and CIPP cured with a removable bladder, air or water exfiltration tests are typically performed. Quality control efforts should also be demonstrated for equipment maintenance and repair in the event of an onsite breakdown.

2.6.10 Timing of submittals

A few guidelines concerning the order and the timing of these submittals are presented in this section. The construction methods, sequencing and scheduling, and safety plan are usually submitted after contract award but before Notice to Proceed, although some description of construction methods and time required for installation may be useful in technical evaluation of the product to prequalify a bid or with the bid package. Construction records are submitted throughout the construction process.

The certifications, qualifications, and quality control plan items can involve partial submittals to prequalify a product or with the bid to evaluate the bid package. Other portions of these submittals are given prior to Notice to Proceed. Some of the quality control items involving sampling of the finished product would be submitted during construction.

In reviewing how these various submittals may apply to a specific project, it is imperative that the items selected be fully addressed in the project specifications with technical requirements given where applicable.

3 Guidelines for Mini-Horizontal Directional Drilling (Mini-HDD)

3.1 Introduction

3.1.1 Scope and approach

These guidelines were developed to assist owners and designers in evaluating current capabilities of the mini-HDD method and to assist in preparing plans and specifications for mini-HDD projects consistent with project requirements and site conditions. These guidelines are intended to help those in the process of designing and specifying pipeline or cable installation projects that may be amenable to construction using mini-HDD methods. The focus of this chapter is on the capabilities of the process used, potential problems, and guidance for avoiding or mitigating common problems, as opposed to prescribed design procedures and specifications. From this chapter, the owner and engineer should gain an appreciation of the important issues and resources available to assist them in developing plans and specifications. It is envisioned that the contractor will also benefit from the development of more uniform, well-thought-out plans and specifications. However, it should be recognized that trenchless technology in general, and mini-HDD specifically, are rapidly growing technologies. These guidelines may require revision and updating as the technology grows and experience is gained.

These guidelines are based on information related to the mini-HDD technique obtained from manufacturers' literature, technical papers, interviews of industry experts, preliminary drafts of utility-specific guides that are being developed by others (e.g., Institute of Electrical and Electronics Engineers (IEEE) Cable Installation Guide) (IEEE 1994)), sample specifications prepared by states and municipalities, the mini-HDD state-of-the-art-review (Khan et al. 1994), and field tests (Bennett, Khan, and Iseley 1994) conducted under the CPAR Program.

3.1.2 General description and range of applications of mini-HDD

With regards to diameter, length, and depth, there are no universally accepted ranges of mini-HDD applications. However, mini-HDD methods are typically used for the installation of small-diameter lines (2- to 10-in. diameter), up to 600 ft in length, and up to 15 ft deep. Some systems can be used for installations as deep as 30 ft. Installations longer than 600 ft are possible, as are larger diameters, but the systems used for these applications are not usually considered to be mini-HDD systems (Khan et al. 1994).

The mini-HDD process involves the creation of a small-diameter (2- to 4-in.) borehole using steerable, fluid-jet-assisted, mechanical cutting tool, and pulling back the utility line through the borehole. The borehole may be, and often is, enlarged with the help of a reaming assembly to accommodate the utility line. Although there are a few dry systems, most mini-HDD systems use a slurry to stabilize the walls of the borehole and to reduce the frictional drag on the cable line or pipeline being installed. Most mini-HDD systems manufactured in the United States use fluid-assisted mechanical cutting technology. Survey systems used for locating the drill head vary with manufacturers, but all locate the drill head position so that steering corrections can be made as the boring progresses. Steering corrections are made in soils by rotating the slanted cutter shoe to the desired orientation and then advancing the shoe and string without rotation. In rock or hard soils, a bent sub is used in conjunction with a downhole mud motor to make steering corrections. Mini-HDD techniques and machines used in the United States are described elsewhere (Khan et al. 1994).

3.2 Applicable References

Listed in the following sections are references, including test standards and reports, that should be useful in developing plans and specifications for projects using mini-HDD methods. This list is intended to identify some of the most recent and commonly used references. Some are in draft stage, as indicated.

3.2.1 American Society for Testing and Materials (ASTM) Standards

(Unless otherwise noted, all ASTM Standards should be for the latest year of publication.)

ASTM C 907	Test Method for Tensile Adhesive Strength of Preformed Tape Sealings by Disk Method
ASTM D 638	Test Method for Tensile Properties of Plastics *(Test Method)*
ASTM D 1248	Specification for Polyethylene Plastics Molding and Extrusion Materials *(Specification)*
ASTM D 1599	Test Method for Short Time Hydraulic Failure Pressure of Plastic Pipe, Tubing, and Fittings *(Test Method)*
ASTM D 3034	Type PSM Poly Vinyl Chloride (PVC) Sewer Pipe and Fittings *(Specification)*
ASTM D 3212	Specification for Joints for Drains and Fuel Plastic Pipes Using Flexible Elastomeric Seals *(Specification)*
ASTM D 3350	Specification for Polyethylene Plastics Pipe and Fitting Materials *(Specification)*
ASTM F 477	Specification for Elastomeric Seals (Gaskets) for Joining Plastic Pipe *(Specification)*

ASTM F 714 Standard Specification for Polyethylene Plastic Pipe Based on Outside Diameter *(Specification)*

3.2.2 American Society of Civil Engineers (ASCE)

Pressure Pipeline Design for Water and Wastewater, Second Edition, 1992.

Tables for the Hydraulic Design of Pipes and Sewers, Fifth Edition, 1990.

3.2.3 American Water Works Association (AWWA) and AWWA Research Foundation

AWWA C 900 Class 150

AWWA C 906 Pressure Class 125

Water Utility Experience with Plastic Service Pipes, AWWA Research Foundation, 1992.

3.2.4 National Sanitation Foundation (NSF)

Standard No. 14 - Plastics Piping System Components and Related Materials, 1988.

3.2.5 Plastics Pipe Institute

Standards for Plastic Piping, September, 1990.

3.2.6 CPAR and related reports

The following resources are available:

a. Bennett, R. D., Khan, S., and Iseley, T. (1994). "Mini-HDD Field Evaluation at WES," Technical Report No. 102, Louisiana Tech University, Ruston, LA.

b. Khan, S., Bennett, D., McCrary, S., and Iseley, T. (1994). "Mini-HDD state-of-the-art review," Technical Report No. 101, Trenchless Technology Center, Louisiana Tech University, Ruston, LA.

c. Khan, S. (1995). "Soil/drilling interaction investigation and guideline development for mini-horizontal directional drilling projects." Masters Thesis, Louisiana Tech University, Ruston, LA.

3.2.7 Institute of Electrical & Electronics Engineers (IEEE) guideline

Draft Guide for Installation of Cable Using the Guided Boring Method, prepared by Working Group 11-28 of the Structures Subcommittee (No. 11), Insulated Conductors Committee of the Institute of Electrical & Electronic Engineers (IEEE) Power Engineering Society, May, 1994.

3.3 Project Planning and Feasibility Issues

Opportunities to add value to and reduce costs of a project are greatest in the early planning and feasibility study phases. Adoption of well-reasoned modifications and value engineering proposals can have beneficial impacts during almost any stage of a project. But the greatest impact is at the beginning stages, as illustrated in Figure 3-1. This figure illustrates the relationship between time, construction costs, and ability to influence costs. The ideas presented in this section are developed in this context. Project requirements and construction methods are inextricably linked. The engineer who understands the applications and limitations of various construction methods can often fine-tune project requirements to allow consideration of innovative methods. Project requirements established without regard to these capabilities and limitations often lead to lost efficiencies and higher costs. Construction methods specified without due regard to capabilities and limitations can lead to stalled projects and claims. For example, if a project is designed as an open-cut job, the route and depth will be strongly influenced by the need to minimize the number of utility relocations, the requirements to ensure worker safety, anticipated dewatering, and trench stabilization requirements. Mini-HDD can be used to install lines below existing utilities, with minimal surface excavations and disruption to surface activities, without the need for dewatering. This offers immense flexibility for the engineer to tailor project design requirements and take advantage of these capabilities. Some projects that may not be considered technically or economically feasible using open-cut construction, might be economically constructed using mini-HDD.

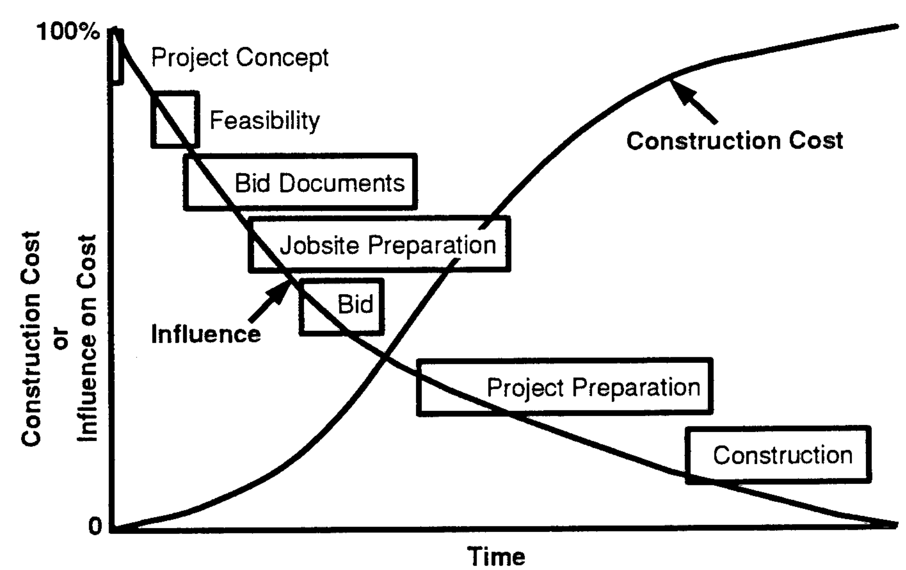

Figure 3-1. Ability to influence construction cost over time

The factors to be considered in the project planning and feasibility study phase include:

a. Construction cost.

b. Other direct costs including restoration and maintenance of street surfaces.

c. Worker safety.

d. Public safety.

e. Site conditions.

f. Environmental constraints.

g. Public inconvenience.

It is recognized that not all of these factors can be assessed quantitatively with available tools, but at a minimum should be at least qualitatively assessed until reliable methods become available to more explicitly evaluate these factors.

3.3.1 Feasibility of mini-HDD method for a project

The feasibility of the mini-HDD technique should be initially established on the basis of diameter, length, degree of accuracy in alignment, and required/achievable grade. Mini-HDD is not currently practical for installing pipe to the precise alignment and grade tolerances required for gravity sewer lines. However, mini-HDD is well-suited for installing new utility networks for water, gas, electric, or telecommunication lines in developed areas. It can also be used for installation of pressure sewer lines. The diameter of the product pipe or utility line to be installed using this technique should be between 2 and 10 in., and depth should usually be less than 30 ft.

Mini-HDD is a surface-launched installation technique that typically uses either controlled-fluid cutting or fluid-assisted mechanical cutting. However, this method can use air for cooling or boring assistance, or can be a dry process where neither liquid (e.g., bentonite/water) nor air is used. Therefore, the choice of fluid-assisted or dry cutting depends on the nature of work (normal utility application or environmental application), size of the utility line (diameter and length), subsurface conditions, and impact on the environment.

The dry system is suitable only for small-diameter (typically less than 4 in.) and short-length (typically less than 150 ft) utility line installations. It is useful for drilling through very soft soil or drilling under a sensitive contaminated site where the probability of contamination movement to groundwater or to the surface is high. It may also be applicable where hazardous or toxic wastes have a high probability of contaminating drilling fluids, which would then require proper disposal. The main drawbacks of dry boring are the limitation of pipe size and overheating of the drill head as the bore diameter and the length of bore increase. Also, it should be remembered that the dry boring (with or without air) system is usually less responsive to steering corrections than fluid-assisted mechanical cutting (IEEE 1994). On the other hand, fluid-assisted mechanical boring is appropriate for most utility applications, and the low drilling fluid volume used is unlikely to cause voids or settlement problems. Moreover, the fluid-assisted mechanical cutting system is very useful for

coarse, saturated, sandy soils where the drilling fluid stabilizes the borehole. An important distinction between fluid-assisted mechanical boring and water jet boring is that the high fluid volume and/or very high pressures used in water jet boring often cause erosion of the soil adjacent to the borehole. Fluid-assisted mechanical boring, with low fluid volume, does not cause significant disturbance to the ground adjacent to the borehole. Water jet boring uses water pressures as high as 15,000 psi for cutting the soil (Naval Civil Engineering Laboratory (NCEL) 1992), while mini-HDD uses water pressure less than 4,500 psi to assist in mechanical cutting by the drill head (Khan et al. 1994).

Another factor that should be considered for selecting the method of installation is the steerability of different techniques. Steerability is most important for curved alignments or where the clear space between existing utility lines is small. It is important to determine the minimum radius of curvature attainable with specified diameter drill pipe and product pipe for each method. The minimum radius of curvature is typically given as 125 ft for 1-1/2-in.-diameter pipe, although some manufacturers state that radii of 42.5 ft for 1-1/4-in. pipe and 30 ft for 1-in. pipe are not unusual (Richard Brinton 1995, personal communication). Drill rod life can be adversely affected by use of sharp bends.

The mini-HDD method is best suited for soils with some cohesion (i.e., clayey soils). The method is also quite successfully used in sandy soils by adding bentonite to the drilling fluid to ensure borehole stability. Hard soils, caliche, shale, limestone, and other rocks typically reduce the drilling rate and increase drilling head wear. The mini-HDD method is not well-suited for gravelly soils (greater than 25-percent gravel sizes). For example, at an environmental drilling project in Hanford, WA, the uncemented formation with cobbles and sand caused difficulty in steering the drill head and led to termination of drilling (Wemple, Meyer, and Layne 1994). In this case, sufficient reactive force could not be developed to cause the wedge-shaped drill head to penetrate the soil. It should be noted that widely heterogeneous formations, such as alluvial fills with caliche, sand, gravel, cobbles, and boulders present difficult challenges to penetration and steering control. Therefore, use of the mini-HDD method in these ground conditions may be inappropriate.

3.3.2 Site investigations

The objectives of site investigations are to assess the feasibility of completing the installations, to minimize the likelihood of damaging existing facilities in the area, and to provide the information needed to allow selection of the most appropriate construction technique and equipment consistent with the site conditions. The extent of site investigations required depends on the location and complexity of the project and the risks associated with the project. Site investigations can be divided into three categories: existing utility network investigation, surface investigation, and subsurface investigation.

3.3.2.1 Existing utility network investigation

To understand the physical constraints of the overall project, types, number, and locations of existing utility lines in the project area should be identified. This can usually be accomplished by notifying the "one-call" center in the project area. This is the regional notification center that keeps track of the presence of utility lines in that area. Most utility companies subscribe to the one-call system. However, in some areas, companies that have underground facilities at or near the jobsite may not be required to subscribe to a one-call service. Those companies that do not subscribe to the one-call system must be identified and notified separately. These investigations should be completed, and regulations covering one-call service or utility notification must be complied with before

construction begins. It is primarily the contractor's responsibility to contact the regional notification center to investigate existing utility lines in that area.

3.3.2.2 Surface investigations

During the surface investigation, site access and available working areas should be determined for the rig set-up area and the product pipe prefabrication area for the utility line to be installed. The rig working area should be reasonably level, firm, and suitable for the movement of rubber-tired vehicles, although track-mounted machines can be used in terrain unsuitable for rubber-tired systems. Locations of surface obstructions that would prevent use of the walk-over technique to locate the drill head should be determined. Also, locations of overhead structures or wire lines should be noted to avoid hazards and facilitate safe equipment movement. It is important to prepare an accurate plan view of the site including these features and any structures planned but not shown on existing maps.

After the route is selected, the entry and exit points should be marked. For longer installations, intermediate drill rig set-up areas and connecting points should be considered. It should be remembered that the horizontal distance between the entry and exit points is less than the length of installed pipe (i.e., the pipe length is always greater than the horizontal distance between entry and exit points). Noise levels associated with mini-HDD projects are not high. However, restrictions on work hours may be required at locations very close to residential buildings, schools, or hospitals. A source of clean water is required for drilling and should be identified. Use of potable water minimizes the likelihood of introducing contaminants that will clog the drill head jets and could have adverse effects on the drilling fluids.

3.3.2.3 Subsurface investigations

The subsurface investigation for typical mini-HDD projects is generally limited to reviewing available geological and geotechnical information to determine soil type, consistency, and groundwater level. This information is used to estimate stability, strength, and permeability. The potential for occurrence of contaminants in the soil, natural or man-made obstacles such as boulders, large construction debris, etc., should be determined using historical records and geologic information. It is unlikely that the locations of all potential obstructions can be reliably established, but all collected information will help define the profile of the bore route with the objectives of avoiding obstructions and excessive curvature in the route of the borehole. Subsurface conditions that cause problems and are not revealed in the contract documents will generally be treated as unforeseen conditions. Any extra costs involved may be claimed for payment as extra work by the contractor.

For large, high risk, or environmentally sensitive projects, detailed subsurface investigations are recommended. Suggested properties to be evaluated include: soil type, unconfined compressive strength, unit weight, particle size gradation, moisture content, plasticity characteristics, permeability of the underlying soil, and water table location. For such projects, abrasiveness, unconfined compressive strength, and rock quality designation (RQD) are needed. Some of this information may be available from published soil reports (e.g., Soil Conservation Service, United States Geographic Survey, U.S. Army Corps of Engineers) and from previous construction projects in the vicinity. A limited number of strategically located borings can then be used to complement available information.

3.4 Design Considerations

Design considerations evolve from project requirements and site conditions and include:

a. Bore layout and profile.

b. Accuracy and tolerance requirements.

c. Mini-HDD system capabilities and selection criteria.

d. Drilling fluid considerations.

e. Drill pipe and drill head considerations.

f. Reaming assembly and pullback operation.

g. Product pipe/utility line considerations.

3.4.1 Bore layout and profile

For installations in relatively level areas without any underground utility lines, a visual survey and simple sketch of the desired route may be sufficient for determining the bore layout and profile. However, for more difficult applications, a transit survey or other type of survey may be required. In general, the bore route plan view and profile should show the surface grade line and locations of important surface features, such as building foundations, underground utility lines, and reference points. Also, the bore route layout should show anticipated lateral utility connections or intersection points, the bore depth at each reference point, and the bore depth at critical points such as utility connection points, existing utility crossings, surface depressions, and course corrections. The planned layout should avoid unnecessary or sharp bends (bend radius smaller than the minimum radius of curvature recommended by the manufacturer for a particular drill pipe and product pipe) and consecutive left and right or upward and downward curves. Sharp curvature and consecutive left/right and upward/downward curves cause increased stresses in both the drill string and the product pipe. Furthermore, steering is more difficult for these types of alignments. In general, bends in any direction should be compatible with the recommended bend radius of the drill rods, as discussed previously.

The typical profile of a mini-HDD bore includes an inclined and vertically curved section at the transition near the entry end (and sometimes at the exit end) and the main "straight" horizontal section for the intermediate length. Often there are small pits at both ends for utility terminations and/or the placement of utility terminals. The horizontal section may necessarily include some curved sections when required to avoid existing obstacles and other utility lines, but care should be taken not to intrude into the rights of way of other utility lines. The depth of cover should typically be a minimum of 3 ft or the depth specified by the utility owner in the horizontal section of the bore route. The minimum depth of cover requirement will help reduce the possibility of drilling fluid leakage to the surface and surface heave. Some State Departments of Transportation (DOTs) require 4 ft of minimum cover measured from the top of the pavement or 3 ft from the lowest point of the surface when drilling under highway rights-of-way (Michigan DOT 1989). The utility owner or engineer

should specify required minimum depths. Excessive depths may complicate future maintenance activities, and specification of maximum depth may be appropriate in such cases.

In designing the bore route, it is of utmost importance to avoid existing utility lines. A minimum clearance between the existing utility lines and the new utility line to be installed should be specified. For example, Louisiana Underground Utilities and Facilities Damage Prevention Law states that the domain of an existing underground utility line is the width (diameter) of that utility line plus 18 in. on either side (Louisiana 1988). This requirement implies that the planned bore should not be within 1-1/2 ft of an existing utility line.

3.4.2 Accuracy and tolerance requirements

Accuracy is freedom from mistake or error, the absolute nearness to truth, i.e, the discrepancy between measurements and truth. Precision is the degree of care or refinement with which measurements are or can be made. Tolerance is the deviation between ideal and achieved (as-built) conditions that can be or is allowed.

When establishing requirements in plans and specifications, it may prove beneficial to review the definitions of these sometimes misinterpreted terms. The owner, through his engineer, must establish the requirements for accuracy of mini-HDD bores. The requirements should be set in terms of allowable horizontal and vertical deviations (tolerances) at entry and exit points and at stated intervals or locations between these points. The tolerances specified must be based on what is required for satisfactory performance and must be balanced against what is reasonably achievable.

Mini-HDD system manufacturers generally provide system specifications that state the accuracy achievable with their locator system. This stated accuracy is usually ± 2 to 5 percent of depth. However, optimum accuracy also depends on use of equipment that is in good working condition, an operator who is qualified and experienced, and operating conditions that are optimal. The precision achievable with a particular locator is but one factor in this equation. The other factors that influence accuracy achievable in the field include the depth, and layout of the bore, topography of the terrain, subsurface conditions including presence of metallic objects, utilities, electronic signals and obstructions, intervals between measurements, and skill and care taken in measurements. Claims are often made that the exit point was within a relatively small distance of the target. Conspicuously absent is any claim about the accuracy of the bore between entry and exit points. The optimistic assumption is that the deviations between planned and actual bore location are no greater at intermediate locations than at the exit, or that it does not matter. This assumption is not usually true. Measurements are almost never made in practice to determine deviations between planned and actual bore locations except at the exit. From a practical point of view, it may indeed be important to control deviations between planned and actual bore locations at intermediate points to minimize the possibility of striking other utilities and to minimize sharp bends in the bore. However, an excavation is required to verify actual location, and a survey measurement is required to establish deviation both horizontally and vertically. Since one of the primary objectives of specifying mini-HDD construction is to minimize excavations and surface disruptions, these actions are seldom taken.

Under normal circumstances, mini-HDD systems should be capable of achieving installation accuracies of ± 12 in. vertically and horizontally. Available third-party test data generally support achievement of this level of accuracy (Bennett, Khan, and Iseley 1994). Higher accuracies (± 6 in.) are possible and have been specified. The engineer faced with developing specifications and

tolerances for mini-HDD projects must somehow take all pertinent factors into account and balance what is reasonably achievable for a given set of conditions against minimum acceptable project requirements. If, for example, project requirements dictate only that a utility be installed from one side of a road to the other, within a 5-ft window, there may be no justification for setting close tolerances that could slow the project and increase costs. Conversely, if it is known that existing utilities are located 2 ft apart, then the tolerances must be established (or the bore be relocated) to avoid hitting them, and greater care will be required during construction. Specifically, when close tolerances are set by the engineer, locator readings and steering corrections must be made more frequently, slowing progress and increasing costs, but this may be a reasonable trade-off. In cases where nearby utilities necessitate use of close tolerances, these tolerances should be required at all points between entry and exit. Requirements should be stated for frequency of locator measurements as well as remedial actions when tolerances are exceeded. Abrupt steering corrections should be avoided to minimize bending and pullback stresses that could lead to breaking off pipes or tools in the hole. The engineer should lay out the route alignment to minimize abrupt changes in direction.

Another important factor that should be considered regarding tolerance is the actual versus mapped locations of existing utility lines. The method with which the existing utilities are located, either from the as-built drawings prepared during construction or by running the locators to determine the position of the line (before starting the drilling), may have a great impact on tolerance. Figure 3-2 shows that the space between two tolerance boxes, one for the existing utility line and the other for the new utility line, may change depending on the actual location of the existing utility line. The goal in developing project specifications should be to ensure that these two boxes (one is for the new and the other is for the existing utility line) do not overlap. It should be noted that the size of each tolerance box may also vary, depending on the degree of accuracy with which the existing utility line's location is known and the tolerances set for the new installation.

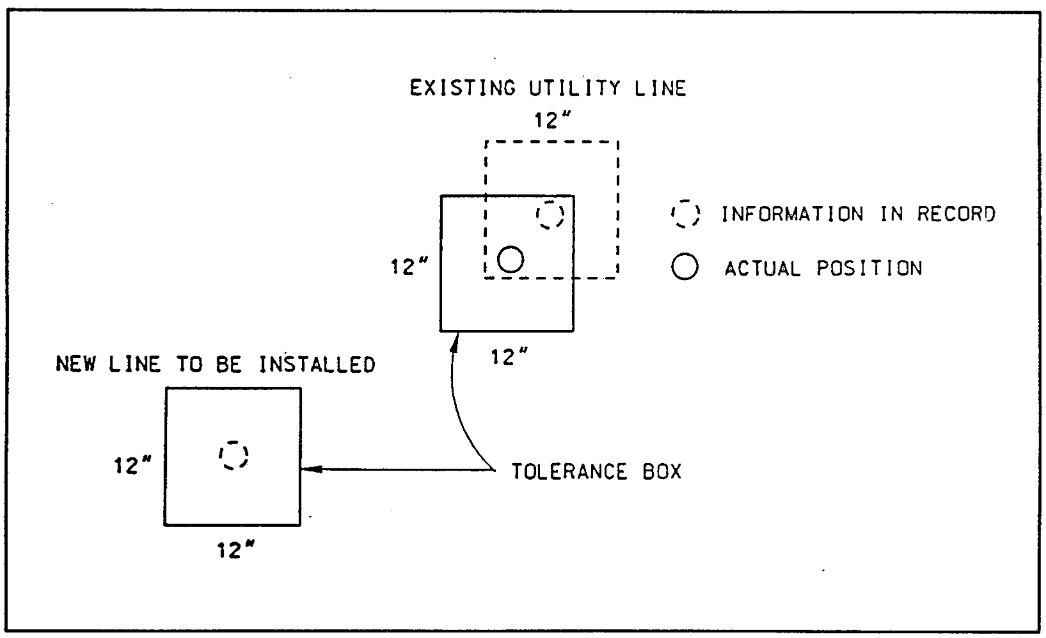

Figure 3-2. Tolerance for existing and new utility lines

3.4.3 Mini-HDD system capabilities and selection criteria

The primary selection criteria for a mini-HDD machine are thrust/pullback and torque capabilities. However, project-related requirements such as length of installation and diameter of the product pipe play an important role in the selection process. Typically, mini-HDD machines have a thrust/pullback and torque capability of less than or equal to 20,000 lb and 950 ft-lb, respectively, and can install pipes of 2- to 10-in. diameter up to 600 ft in length, depending on soil conditions. Installation depth is limited to less than 30 ft, in general, due to locator limitations. However, some manufacturers claim that installations can be as deep as 50 ft without hardwired transmitters and 75 ft or greater with hardwired transmitters (Richard Brinton 1995, personal communication). At congested sites, the area required by the complete drilling package is an important consideration that should be balanced against estimated power requirements.

The type of locating system used to locate the cutting head is an important consideration because of variations in surface accessibility. Most mini-HDD systems rely on "walk-over" locator systems. However, for deep installations or for limited surface access, wire line or wireless tracking systems may be required. For a site suspected of having magnetic interferences, a surface grid system can be used in conjunction with the downhole locating tool to improve the locating capability. For projects in rock, a mud motor is required to operate the drill bit for cutting and penetrating the formation. Finally, the productivity and the price of the system including all the accessories and other optional features are important selection factors. Trade-offs may be necessary between capital cost, productivity gains, and utilization rates.

3.4.4 Drilling fluid considerations

The primary functions of drilling fluids are to:

a. Stabilize the borehole.

b. Reduce torque on drill pipe.

c. Reduce pullback force on product pipe and drill pipe.

d. Cool the drill bit and transmitter.

e. Clean cuttings from the drill bit.

f. Form a filter cake on the borehole walls to reduce fluid losses into surrounding soil.

g. Control groundwater pressures.

h. Reduce wear of the drilling equipment.

i. Provide steering capability by jet cutting.

Trade-offs are often required to satisfy all these drilling fluid functions and control the choices with regard to the type of drilling fluid, volume, and pressure.

3.4.4.1 Type of drilling fluid

Depending on soil conditions, water only or water mixed with bentonite and/or polymer can be used as a drilling fluid in a directional drilling application. Water alone is normally suitable for drilling in silty or clayey soils. If a highly plastic or expansive clay is encountered, polymer mixed with water will improve the hole lubrication and reduce the swelling tendency of clay (swelling tends to close off the hole, which increases torque and pullback requirements). For example, for highly plastic clay-type soils, 1 qt of liquid polymer per 100 gal of fresh water is typically recommended (Straightline Manufacturing, Inc. 1993). For sand or other poorly consolidated formations, a bentonite mixture with a Marsh funnel viscosity ranging from 35 to 50 sec/qt will generally form a slurry with sufficient strength to support the borehole. However, the drilling rate may have to be reduced to achieve this effect. When the drill string is withdrawn to pull in the utility line or backream a larger borehole, a drilling fluid Marsh funnel viscosity of 35 sec/qt or considerably higher for sands is recommended for lubrication and to aid in maintaining an open borehole.

The amount of drilling additives (bentonite or polymer) depends on soil conditions. For normal soil conditions, 15 to 25 lb of bentonite per 100 gal of water is sufficient, and for difficult soils, such as coarse saturated sand, 25 to 40 lb of bentonite per 100 gal of water is recommended. For more difficult drilling jobs, a mixture of both bentonite and polymer may be used, typically, 15 lb of bentonite and 1 pt of liquid polymer per 100 gal of water (Straightline Manufacturing, Inc. 1993). The specific gravity of bentonite-mixed drilling fluid should range from 1.02 to 1.03.

The water used in the drilling fluid should not be hard or salty because this will cause poor mixing or yield with the bentonite or polymer and the flocculated bentonite may tend to settle to the bottom of the tank. Hard water should be treated with soda ash using 0.5 to 2 lb/100 gal of water (Straightline Manufacturing, Inc. 1993), and salty water should be avoided.

3.4.4.2 Volume and pressure requirements

3.4.4.2.1 *Drilling fluid volume.* For most mini-HDD projects, the typical drilling fluid flow rate used is 1 to 3 gal/min for pilot hole boring operations and 4 to 8 gal/min for pullback operations, with clayey soils generally requiring the lowest and sandy soils generally requiring the highest values mentioned. The volume of drilling fluid required for a particular project depends on the length and diameter of pipe to be installed and the soil type. The volume is typically estimated as equal to the volume of the borehole, although some losses occur. The average drilling fluid usage rate can be calculated after the installation is completed based on the total fluid used and the length of bore and should be recorded as average flow rate in gallons per foot of bore. It should be noted, however, that the fluid usage rate will also vary with particular machine design and operator experience and choice. Usage of drilling fluid for pilot hole boring in the WES tests and in the Orlando demonstration was 0.5 to 1.3 gal/ft of bore for silt and 0.5 to 0.8 gal/ft of bore for silty sand conditions. During the pullback operation, the usage was 0.8 to 1.1 gal/ft of bore for silt and 0.9 to 1.0 gal/ft of bore for silty sand condition (Bennett, Khan, Iseley 1994). In both cases, the pilot hole was approximately 3 to 4 in. in diameter, and the reaming borehole diameter was approximately 6 to 8 in. The product pipe outside diameter was 4-1/2 to 5-1/2 in. From these particular tests, it was observed that the fluid usage was about the same for both the pilot hole boring and the pullback operation. However, reaming typically requires higher fluid usage.

Currently, all the mini-HDD systems measure the volume of drilling fluid pumped in gallons per minute (gpm), which does not help much in estimating the amount of fluid used per foot of bore because of the unpredictable intermittent time of actual drilling. Typically, the total volume used for the entire bore is measured for pilot hole boring and for product pipe pullback, from the capacity of the tank which includes all the losses (e.g., loss during pipe break-out and loss near entry or exit point) during the operation. However, proper control and measurement of drilling fluid are desirable to ensure the optimum delivery of fluid into the hole under given soil conditions. Flow measuring devices may be used to effectively measure and control the cumulative fluid volume used as the bore progresses during both the pilot hole drilling and reaming operations. This information would be useful for estimating the volume of fluid needed for future projects. More importantly, sudden increases or decreases could indicate voids or other ground conditions that should be identified so that drilling methods can be modified, as needed, to complete the bore. For example, the slurry viscosity or pressure may require adjustment to cope with encountered conditions.

3.4.4.2.2 *Drilling fluid pressure.* For fluid-assisted mechanical cutting (termed as mini-HDD), the low fluid volume and relatively low (2,000 to 4,000 psi) operational pressures minimize potential problems commonly associated with the water jet boring method in which high pressure water jets erode the soil around the drill head forming the hole (NCEL 1992). For mini-HDD installations, the magnitude of the drilling fluid pressure is not a major concern in this regard because of the relatively low fluid volumes. However, the pressures are sufficiently high to cause injury, so safety precautions must be observed. Currently available mini-HDD systems are capable of producing maximum drilling fluid pressure from 1,500 to 4,500 psi at the drill rig, although not necessarily at the drill head where soil cutting is accomplished. The drilling fluid pressure drops with distance approximately 1/2 psi for each foot of 1-1/2-in.-diameter drill pipe. Effective drilling fluid pressure at the drill head depends on the diameter of the product pipe, viscosity of the fluid, fluid flow rate (gpm), and the number and size of nozzles (orifices) at the drill head.

For most soils, operating pressures from 300 to 1,400 psi at the drill head are sufficient to maintain proper fluid flow. For harder soil formations, the higher range of operating pressures (1,400 to 4,000 psi) may work best. For unstable soils (e.g., unconsolidated sand), low operating pressures of 300 to 500 psi often would be suitable to control seepage and hole cutting (Ditch Witch 1993). It is emphasized that higher fluid pressures are not necessarily detrimental for many soil conditions. A drilling fluid pressure of 3,000 psi was applied in a mini-HDD demonstration at Conway Springs, AR, under very stiff clay conditions with no sign of soil erosion from the bore (Iseley 1992). Also, in the WES tests, no significant soil disturbance was observed around the borehole in clay, clay-gravel, sand, and silt, even though the drilling fluid pressures at those locations ranged up to 3,000 psi (Bennett, Khan, and Iseley 1994).

3.4.5 Drill pipe and drill head considerations

3.4.5.1 Drill pipe

The drill pipe (drill stem) is subjected to tensile, compressive, bending, torsional, and thermal stresses during the cyclic construction processes. A careful engineering analysis and care in use are essential to ensure long life of the drill pipe for future operations. The material used for the drill pipe should have good strength properties and be relatively smooth on its outside surface. The loads and stresses generated during the drilling operations will depend upon several factors described in the following:

3.4.5.1.1 *Tensile loading*. Tension in the drill pipe develops mainly during pullback due to the frictional force on the drill string and product pipe, the resistive force at the cutting face of the reaming assembly, and the bending resistance of the pipe section (both drill pipe and product pipe). Considering all these factors, it is impractical to attempt to calculate the exact tension developed in the drill string. However, it is necessary that the drill pipe should have a tensile capacity at least 2 to 3 times the maximum thrust or pullback capability of the drill rig to account for the loads that are difficult to estimate.

3.4.5.1.2 *Compressive loading*. Compression in the drill pipe develops during the pilot hole boring process, but also due to bending during operations. However, compressive stresses are usually not critical for design.

3.4.5.1.3 *Bending loading*. Drill pipe bending resulting from curved alignment or from over-steering (large deviations or sharp turns at the entry pit) will cause bending stresses (both tensile and compressive). Rotation of the drill string will cause stress cycling and eventual fatigue failure at these bend areas. The installed product pipe also must have sufficient strength and flexibility to withstand stresses that develop when it passes through curves or bends of the borehole.

The bend radius of the bore route should be within the allowable limit of the drill pipe minimum radius of curvature so that it will not cause overstressing of the drill pipe or product pipe. The actual bending stresses developed in the drill pipe may be calculated as

$$f_s = \frac{E \times D}{2R\ (12)} \tag{1}$$

where

f_s = peak tensile (or compression) stress developed in pipe (psi)

E = modulus of elasticity (psi)

D = pipe outside diameter (in.)

R = radius of curvature of bends (ft)

Usually, the bending stress f_s for a given drill pipe is proportional to the bending radius (e.g., for steel); a suggested minimum drill pipe bending radius is $R \geq 100 \times D$ (McKelvie, Cayton, and Tyhurst 1992).

3.4.5.1.4 *Torsion loading*. Torsion develops from the rotating action of the drill string and the resistance of the soil. The drill pipe, especially the joints, must be strong enough to sustain the torsional stress that develops. Typically, torsional loads are highest during the reaming operation. Drilling through hard soil would cause more torsional stress to be developed in the pipe. Similar to the tensile capacity requirements, the drill pipe (including joints) should have a torsional capacity at least equal to the torque capability of the drill rig with an appropriate factor of safety.

3.4.5.1.5 *Thermal loading*. Thermal stress is induced by the mechanical heat developed from the drilling action. For mini-HDD projects the thermal stress is not a significant problem. But, the thermal stress may be calculated as follows:

$$f_t = E \times k \, (T_2 - T_1) \tag{2}$$

where

f_t = thermal stress in pipe (psi)

E = modulus of elasticity (psi)

k = linear coefficient of thermal expansion (in./in./°F)

T_1, T_2 = initial and final drill pipe temperature (°F), respectively

3.4.5.1.6 *Drill pipe selection*. The preferred and most often used material for drill pipe is steel because of its high strength and ductility characteristics. After consideration of all the possible stresses (e.g., tension, bending, torsion, and thermal) that may be imposed, the drill pipe diameter, wall thickness, and steel grade must be selected for compatibility. The most commonly used drill pipe for mini-HDD applications has an outside diameter ranging from 1-1/4 to 2-7/8 in. (McKenney 1994). A typical drill rod is 10 ft long with a wall thickness of 1/4 in. However, other sizes such as 5- or 6-ft-long sections are also available with different mini-HDD systems. The pipe joints should be flush, and the outer surface should be smooth to minimize resistance during both the boring and pullback operation. A variety of anticorrosion coatings are available to prevent corrosion of the steel drill pipe.

3.4.5.2 Drill head

Different designs of drill heads include compaction heads, cutting heads, and various combinations. A compaction head is useful for soft soil, and a cutting head is appropriate for tougher soils. The slanted configuration of the drill head facilitates steering. Drill heads have fluid jet openings through which drilling fluid flows. The operation of the drilling fluid jets assists cutting, borehole stabilization, drill bit and transmitter sonde cooling, and drill pipe lubrication. Typically, for mini-HDD applications, a 2- to 4-in. drill head is used. A wider steering surface is used in soft soils because of the relatively low resistance provided by the soil to induce directional changes. Conversely, for hard soils, a narrower steering surface should be used because of the high resistance provided by the soil. Furthermore, a wide drill head in hard soil would require greater torque to rotate the drill head and may reduce productivity. Therefore, care should be taken to select the appropriate drill head for anticipated soil conditions. In general, a 4-in. drill head would be appropriate for sand, and a 3-in. drill head may be used for clay or average soil conditions. Figure 3-3 shows a typical cutting-type drill head.

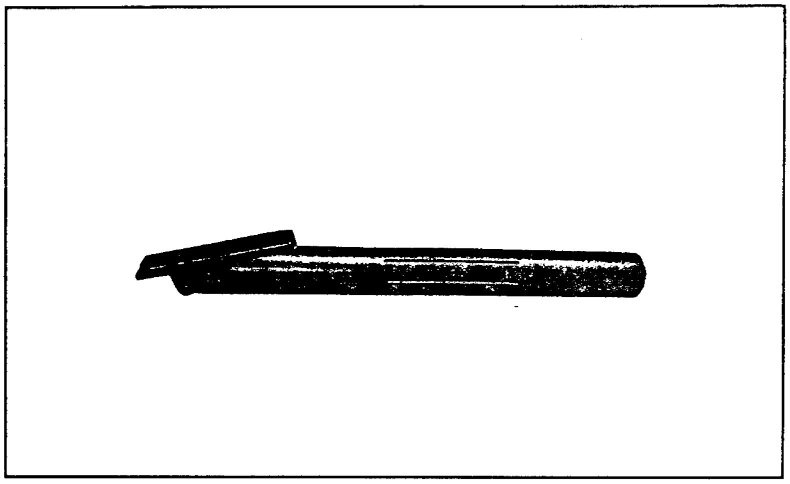

Figure 3-3. Cutting-type drill head

3.4.6 Reaming assembly and pullback operation

3.4.6.1 Reaming assembly

The reaming assembly consists of circular cutters, compactors, and swivels. Typically, circular cutters (reamers) are attached to the drill pipe by replacing the drill head. A swivel mechanism is usually provided between the cutter and the compactor, which prevents rotation of the compactor. A second swivel is attached between the compactor and the product pipe gripper. This swivel prevents the rotation of the drill string from being transmitted to the product pipe. However, since the swivels are not completely efficient, torsion may be transmitted to the pulled section, but this is usually not a problem. The swivel should be in good condition and sized to be compatible with the torsional resistance of the product pipe.

Reamers have fluid jet openings through which drilling fluid flows to facilitate cutting, stabilize the enlarged hole, and lubricate the trailing pipe. Different types of reamers are available including cutting, tri-action, compaction (or packer), barrel, blade reamers, or combinations. Sometimes cutting and compacting action is done by one assembly. Many reamers have carbide cutter bits that assist cutting in a wide variety of soil conditions. The soil condition will determine the specific type of reamer that should be selected. Figure 3-4 shows different types of reamers used under various ground conditions.

The diameter of mini-HDD reamers varies from approximately 4 to 12 in. The compactor diameter is several inches less than the overall reamer diameter (i.e., when a compactor is used separately with the cutter). In general, the reamed hole diameter should be at least 1.5 times the product pipe diameter (IEEE 1994). For example, for a 4-in.-diameter product pipe installation, the overall reamer (cutter) diameter should be approximately 6 in.

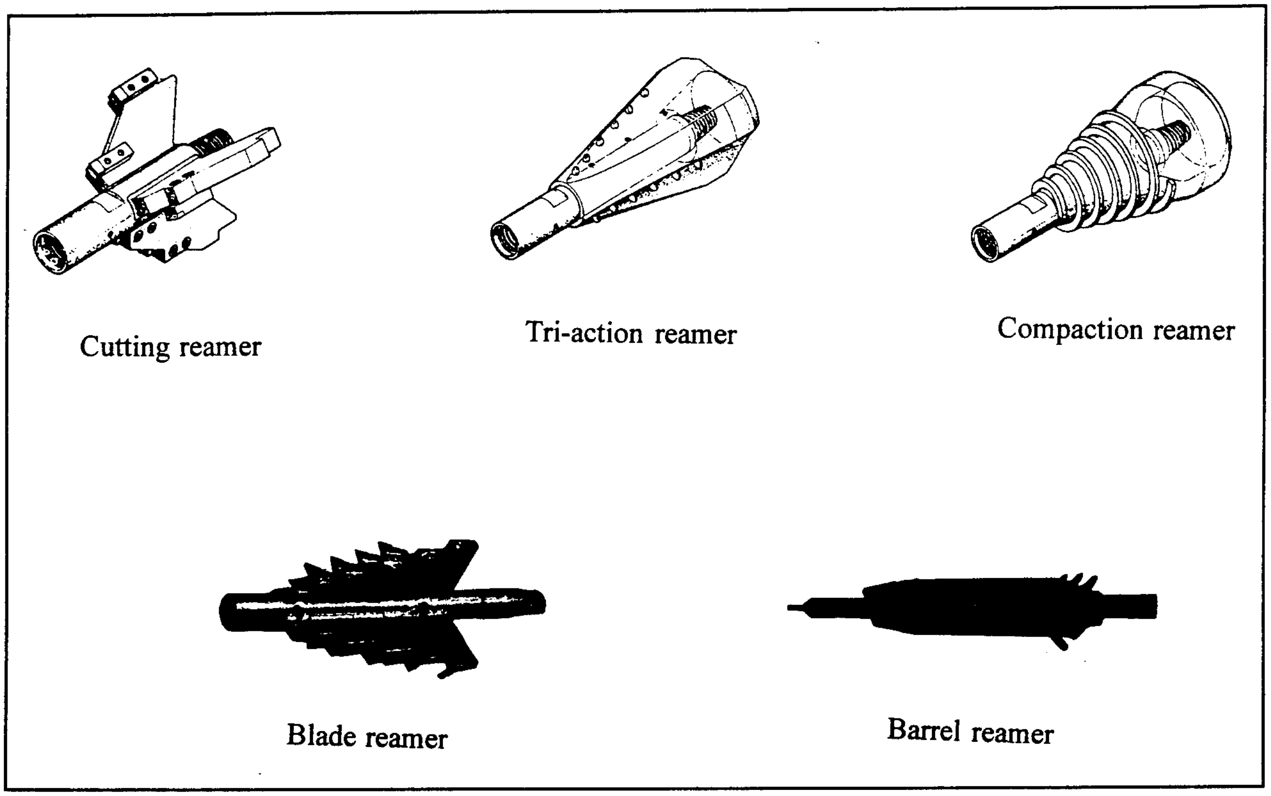

Figure 3-4. Different types of reamers

3.4.6.2 Pullback operation

The pullback operation is the process by which the product pipe or utility line is installed. The pipe is attached behind the reamer assembly, or possibly for a small product line directly to a swivel replacing the drill head. A gripper is connected to the swivel and holds the product pipe while it is pulled into the borehole. Several types of grippers are available, including adapter, pulling-eye, and basket types, or duct puller, as shown in Figure 3-5. An internal adapter-type gripper is fixed inside a hollow pipe without any perforation of the pipe, usually with a threaded male insert. Some adapter types use a gripping mechanism in which the inner and outer surfaces of the pipe are squeezed between two collars inserted over the end of the hollow pipe. A pulling-eye-type gripper is fixed to the inside of the pipe by creating holes in a hollow pipe through which bolts are inserted or by a crimped/swaged connection to the external pipe or cable surface. HDPE and PVC pipes are usually pulled back using adapter or pulling-eye-type grippers. A basket-type gripper is useful for pulling electrical power cables and copper telephone cables and may also be used for installing plastic pipe. Basket-type grippers are made of high-quality galvanized steel strand. A separate basket gripper, of appropriate size range, should be used for each cable or pipe when a bundle of items is to be pulled into the borehole. If external-type pulling-eye or basket grippers are to be used for a hollow plastic pipe, an internal stiffener should be inserted into the end of the pipe.

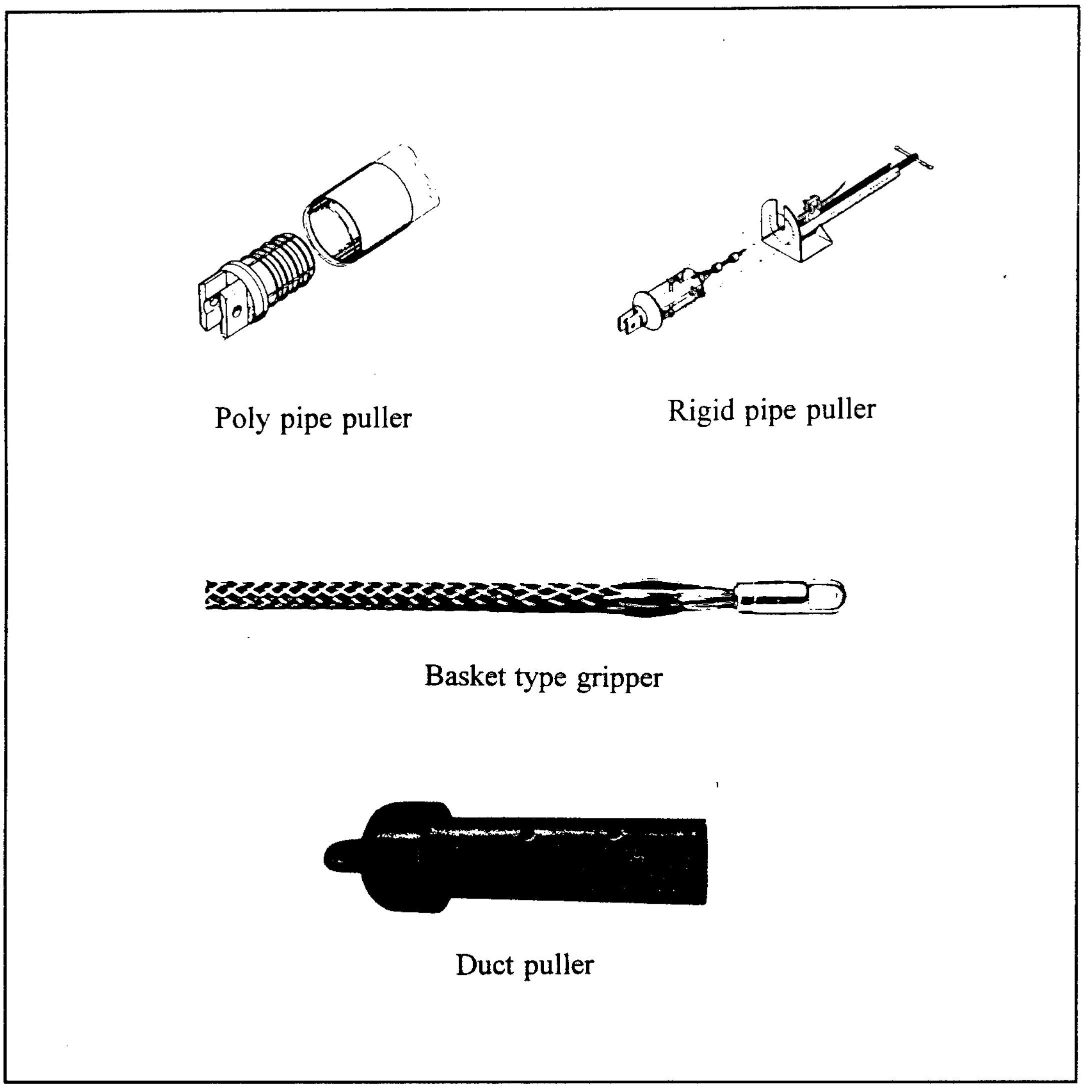

Figure 3-5. Different types of gripper systems

3.4.7 Product pipe/utility line considerations

3.4.7.1 Types and materials of product pipes/utility lines

Any type of cable or small-diameter pipeline that can sustain the tensile forces arising from the pulling action can be installed by the mini-HDD method. Among the most common product pipes used are HDPE, PVC, steel (for small-diameter pipes), and copper (for service lines). Potentially vulnerable (e.g, fiber-optic) cables should not be pulled directly, but may be contained inside the product pipe (e.g., HDPE pipe) during the pulling operations or may be carefully placed after installing the host pipe. The product pipe or utility line should be installed in one continuous operation, preferably without pause, and should protrude a sufficient distance beyond the exit and entry points to allow proper termination or connection at a later time, as required. Rigid PVC

pressure pipes are available in short lengths of typically 10 to 20 ft. PVC pipes used for water and sewer applications should meet the requirements of AWWA C 900 Class 150. HDPE pipes are available as continuous coilable ducts in sizes up to several inches in diameter or in separate lengths of 20 or 40 ft, which can be thermally butt-fused into a continuous length prior to pullback. HDPE pipes should conform to the requirements of AWWA C 906 Pressure Class 125. The minimum bending radius that can be applied to HDPE pipe without kinking varies with the diameter and wall thickness. These pipes may be cold-bent to a radius as small as 20 to 40 times the pipe diameter (Phillips Driscopipe, Inc. 1993).

3.4.7.2 Joints

For HDPE pipes, each section may be joined by the heat-fusion technique, commonly called "butt fusion," to fabricate the complete length ready for mini-HDD installation. The joining technique used should be in accordance with the pipe manufacturer's recommendations for the intended applications, including installation and later usage. The butt-fusion equipment should be capable of meeting all the conditions recommended by the pipe manufacturers including temperature requirements of 400 °F, alignment, and 75 psi interfacial fusion pressure (Phillips Driscopipe, Inc. 1993).

PVC pipe joints must be made such that there is no significant increase in pipe outside diameter at the joint. When the gasket joint system is used, it should meet the requirements of ASTM D 3212. Gasket material should meet ASTM F 477. For PVC pipes, pressure fittings should conform to AWWA C 907. Pipe coupling fittings should have elastomeric gasket joints equipped with integral self-restrained spline locked joints suitable for pulling without disengagement (Roman 1994). Couplings or joints in PVC pipes can be the weak points along the conduit assembly, so the entire conduit should be prestressed before installation. Prestressing is accomplished by inserting steel cable or rod inside the conduit assembly and attaching it at both ends of the conduit. When the steel cable or rod is tensioned during pullback, the joints or couplings remain under compression, which minimizes the risk of joint failure. For steel pipe, the joint may be welded or assembled with sleeve couplings, provided the sleeve is of only slightly greater diameter than the pipe.

3.4.7.3 Product pipe/utility line handling

The product pipe should be stored on clean ground to minimize the potential for scratching or gouging. The pipe should be handled in such a manner that it is not damaged. For direct cable installation, it is desirable that the cable be properly jacketed to avoid damage. When it is necessary to take slack cable off the reel, it should be placed on grassy or smooth soil surfaces, avoiding areas where it may be subjected to damage from pedestrian or vehicular traffic. During the pullback process, a "weak" link (or mechanical fuse) that would break at a known safe tension should be inserted between the cable and the drill string to avoid excessive tension in the cable (IEEE 1994).

3.4.7.4 Testing requirements for product pipe or cable

3.4.7.4.1 *HDPE and PVC pipes.* Before the pullback operation, HDPE and PVC pipes used for gravity or pressure flow should be tested in accordance with the application requirements and specifications of the engineer and the pipe manufacturer. For example, when waterlines are installed, the complete pipeline section should be joined and then flushed and pressure tested. Several types of tests may be required or desirable for waterlines, including air hydrostatic tests of each joint (e.g.,

pipes are fuse-joined), hydrostatic, and leakage tests of the assembled pipeline sections. For some applications, air hydrostatic tests may be applied to the pipeline for 1 hr at 150 psi before pullback (Roman 1994). Individual joints should be checked to detect leaks using leak detection soap solutions. Sections surrounding faulty joints should be removed, new joints should be made, and the sections should then be retested until satisfactory results are attained. Hydrostatic water and leakage tests should be performed following procedures similar to that of the air test.

3.4.7.4.2 *Cables.* Cable should be inspected for cuts or nicks in the outer jacket. Cables with flaws and irregularities should not be installed without approval from the utility owner. Footage markers at the cable end should be recorded for future reference. When the cable is installed with a basket grip, the end of the cable should be covered with a snug cable or electrical tape to prevent water entry.

3.5 Construction Considerations

The construction stage of a mini-HDD project begins with notification and continues through the tracking and marking of existing lines, positioning of the drill unit, and the boring and subsequent reaming and pullback operations. During the process, unforeseen obstructions may be encountered that must be dealt with. In addition, it is necessary to periodically locate and track the drill head position and make steering corrections, as required.

3.5.1 Notification

Adequate notice of the drilling operation should be given to the notification center(s) in that region. For example, the State of Louisiana requires notification at least 48 hr, but not more than 120 hr in advance of actual construction, excluding weekends and holidays (Louisiana Revised Statute of 1950 1988).

3.5.2 Tracking and marking of existing lines

Buried underground hazards including storage tanks, electrical cables, natural gas lines, waterlines, pipes carrying other chemicals, telecommunication cables, and CATV cables must be identified, located, and avoided. Utility- and metal-locating equipment should be used to sweep the area within 20 ft on either side of the bore path. Test pits (potholes) should be dug to determine the actual location of existing utilities handling electricity or gas, oil, petroleum products or other flammable, toxic, or corrosive fluid/gases. The location and type of underground facility should be marked by the utility operator (utility owner) or his representative. Facilities should be visibly marked by color-coded paint, flags, stakes, or similar means using the American Public Works Association (APWA) color code. If the utility operator does not visibly mark the location of these utilities, information should be provided to enable the contractor, using reasonable and prudent means, to determine the approximate location of the utility. The information provided should include a contact person and telephone number.

3.5.3 Positioning of drill unit

The positioning of the drill unit should be such that the required depth starting from the entry point can be achieved. The drill unit should be set up at an appropriate "setback" distance from the point where the required bore depth is desired, with a particular entry angle. Figure 3-6 shows the setback distance from the driveway to the drill rig, a distance of 8 to 10 ft, required to get to the desired depth of 2 to 3 ft under the driveway. Setback distance depends on the pipe diameter, entry angle, and depth. Greater setback distances are required for greater bore depths and diameters. Typically, the pipe diameter, entry angle, for a mini-HDD bore should be in the range of 5 to 20 deg, depending on topographical conditions and depth requirements, but larger and smaller entry angles are possible. Shallower bore angles and longer setback distances will allow less bending of the drill rods. For example, it was observed in the Orlando mini-HDD field demonstrations that relatively short setback distances and steep entry angles resulted in sharper bends or greater depths than intended at the point where the horizontal section of the borehole started (Khan 1995).

The anchoring of the drill unit should be sufficiently rigid to minimize movement of the drill unit during the initial boring and backreaming processes. For soft soils, proper anchoring procedures are particularly important. Most mini-HDD systems use a power stake-down auger for anchoring purposes.

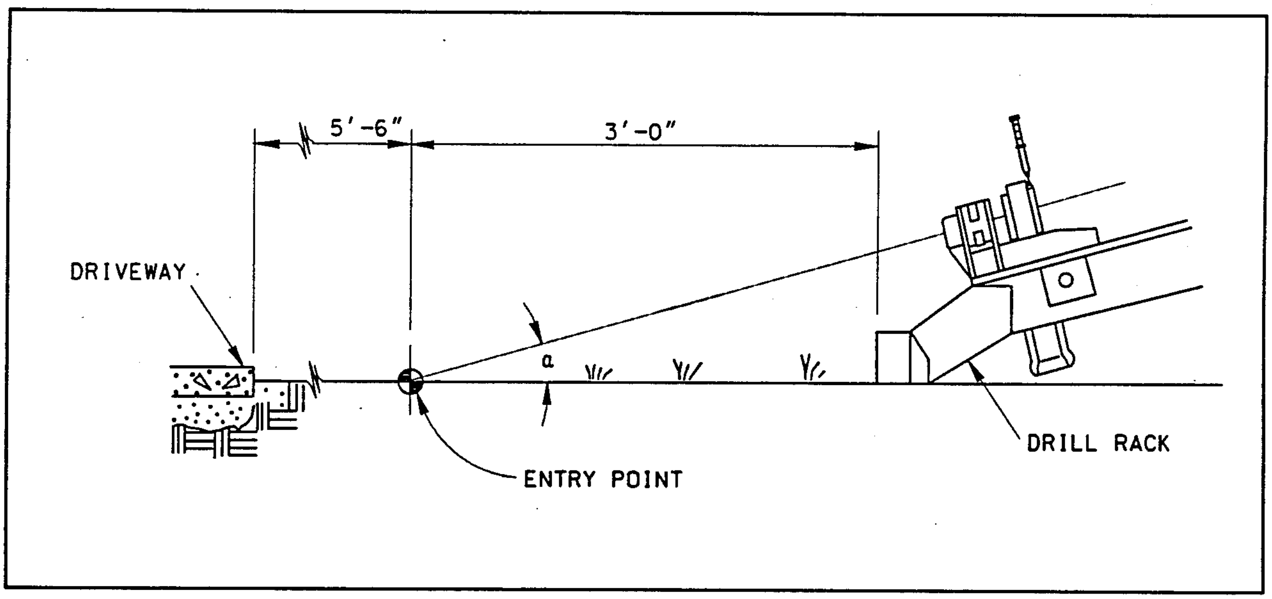

Figure 3-6. Setback distance and entry angle for mini-HDD system

3.5.4 Boring and reaming

Mini-HDD is usually a two-stage process consisting of pilot hole boring and reaming and product pipe pullback. Typically, each stage can be accomplished in a single pass. Depending on the type and diameter of product pipe, length of bore, and soil conditions, the contractor may elect to carry out one or more pre-reams of the drilled borehole. The number of passes and size of reamer usually

should be left to the discretion of the contractor. In general, for product pipes up to approximately 4-in. diameter, pre-reaming is not needed, but for larger sizes pre-reaming can be helpful in reducing the pullback force and torque required to accommodate the final product pipe installation. The enlargement of the drilled borehole by reaming or pre-reaming reduces the possibility of cavity or void formation and future subsidence. The final diameter of the borehole should be at least 50 percent larger than the outside diameter of the product pipe (IEEE 1994; Roman 1994).

The analysis and comparison of the WES field test (Bennett, Khan, and Iseley 1994; Khan 1995) and Orlando field demonstrations (Khan 1995) indicated that the pullback force and torque required for the same mini-HDD system to pull back one 4-1/2-in. outside-diameter HDPE pipe was significantly less than that required for the pullback of a bundle of five 1-1/4-in. HDPE pipes (equivalent to approximately 5-1/2-in. outside diameter), as might be expected. Furthermore, the installation of the bundle of five 1-1/4-in. HDPE pipes experienced more difficulties, including joint disengagement between the reaming assembly and the product pipe. In this case, pre-reaming may have been effective in reducing pullback force and torque and in eliminating the subsequent separation problems. However, it should be noted that the pre-reaming process uses more drilling fluid because the hole is reamed more than once. It was observed in the Orlando field demonstrations that a pre-reamed borehole to pull back 4-1/4-in.-diameter HDPE pipe had a final influence zone (radial extension of drilling fluid beyond the borehole) of 10 in., while a single reamed borehole to pullback 5-1/2-in.-diameter HDPE pipe had only a 1-1/2-in. influence zone in the same type of soil.

For utility line installations of 2-in.-diameter or less, a reamer attachment may not be needed. For example, some types of cables (power lines) may be directly connected to a swivel that replaces the drill head, and pulled back through the pilot borehole.

3.5.5 Locating technique

The most widely used locating technique for mini-HDD is the walk-over surface locator system. In this system, a downhole transmitter or sonde (contained inside the drill head housing) transmits a signal to an electronic receiver unit carried by the locator operator to determine location and depth of the downhole drill head. Typical locating technique is shown in Figure 3-7, with the operator and locator above the downhole transmitter obtaining a depth reading of 36 in. The receiver determines pitch and roll; some units also measure temperature of the drill head and the battery charge. On projects where tolerances are small, locator readings at 5-ft intervals are generally recommended. If the bore route is complicated and passes in the vicinity of other utility lines, more closely spaced locating points may be necessary. For straight simple bores, locator readings may be taken at 10-ft intervals or greater, depending on the required accuracy and crew skill.

3.5.6 Inspection and acceptance

Inspections are essential to ensure compliance with contract specifications and required quality of the finished work. The engineer representing the owner should be knowledgable about the drilling and completion process and should be able to determine if the information provided by the contractor is correct. The engineer should work with the contractor to make sure that the installation is within acceptable tolerances and that the information submitted for preparation of as-built drawings accurately reflects the location of the product pipe or utility line.

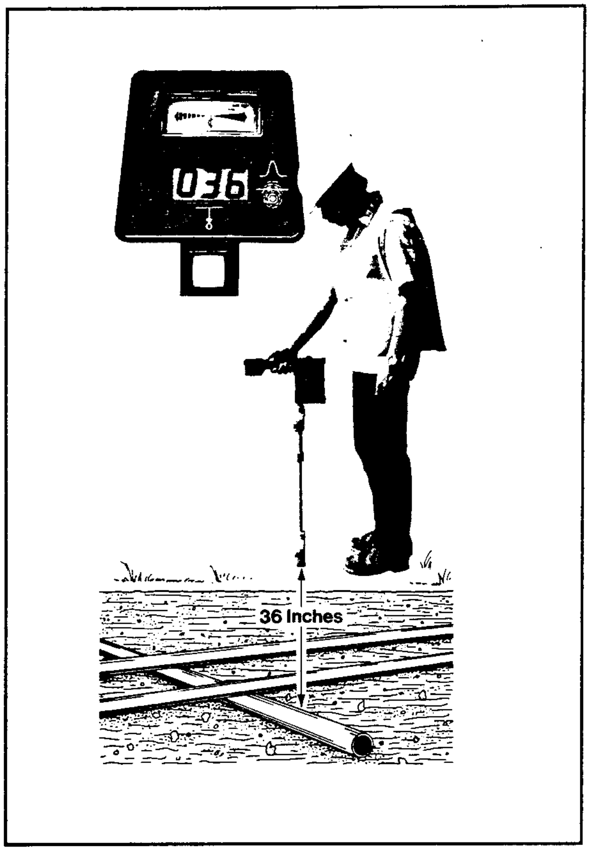

Figure 3-7. Example of "walk-over" locator technique for mini-HDD installations

The engineer should recognize that a potential problem may exist if the pilot hole exits within the target area, but at an angle indicating a large deviation might have occurred before the exit point. Furthermore, if final inspection reveals leakage in installed water or sewer lines or problems with the structural integrity for installed cable conduits, liquidated damages should be assessed using a damage-assessment schedule.

The new product pipe or utility lines should also be inspected for possible damage that may have occurred during the pullback operation. For example, electric power or copper telecommunication cables may be tested by a Megger-insulation resistance check between the conductors/metallic shield and ground to help verify the cable insulation/jacket is sound (IEEE 1994). To verify structural integrity of installed polyethylene or plastic pipe, a mandrel may be pulled through the pipe to identify any structural disorder. For water or sewer lines, the pipe should pass the hydrostatic and leakage tests discussed previously.

3.5.7 Site cleanup

Any migration or spilling of drilling fluid at the surface or into adjacent streets and storm drains must be promptly contained and cleaned. All excavations must be backfilled and properly compacted.

For water or gas lines, no backfill should be placed in pits, trenches, or other excavations until the line has been inspected and passed hydrostatic and leakage tests. After the job has been completed, the surface area should be restored to its original condition.

3.5.8 Safety concerns

During the drilling process, health and safety conditions are of utmost importance and must be monitored and carefully maintained. The contractor must make decisions as to when safety levels require changes in personnel safety attire and when conditions demand a work shutdown. Law, ordinances, and regulations that include environmental and occupational safety concerns must be identified and followed. Hazardous materials must be handled as stated in the MSDS, and direct human exposure to those materials should be avoided.

Requirements for working on a jobsite containing electrical utilities should include an electrical alarm system and grid mats placed to insulate crews from the ground. Appropriate boots, gloves, eye protection glass, and other appropriate protective gear should be used. When working near highways or other areas with traffic, high-visibility clothing, barriers, flagmen, etc., should be used to avoid accidents and maintain traffic flow.

Adequate communications must be established and maintained between the drilling machine operator and the locator operator. Radio communication should be used for longer distances or beyond line-of-sight drilling. If communications are disconnected, the drilling must be halted until the communication is re-established.

3.6 Bid Documents

3.6.1 General

The bid documents, prepared by the owner/engineer, should provide the contractor with all vital information needed to prepare competitive bids for construction. Typical bid documents should include the following: Invitation for Bids, Scope of Work, Plans, Specifications, Site Investigation Report, Procedures for Protecting Existing Structures and Site Features, Inspection Procedures, Minimum Performance Requirements, and Performance Period. However, since mini-HDD is a specialized installation technique, some of the bid documents will have unique requirements. These special requirements are detailed in the following section.

3.6.2 Minimum performance requirements and performance period

Minimum performance requirements are established in the contract documents to ensure that the pipeline, as installed, will perform as designed. The primary criteria typically established for gauging performance include pipeline location, hydraulic characteristics, water infiltration, internal pressure tests, and protection of adjacent structures, other utilities, building foundations, streets, roadways, bridges, tunnels, rail-lines, etc.

Secondary criteria are often established to guide the contractor and ensure that the primary criteria are satisfied. Secondary criteria may include allowable settlement/heave, fluid pressures, flow rates, minimum depth of cover, allowable work hours, and safety requirements.

3.6.3 List of applicable references and standards

A list of references and standards for equipment, materials, safety, etc., should be provided to the contractor for use in planning and bid presentation.

3.6.4 Site-investigation report

All site-investigation information, including existing utility network investigation, surface investigation and subsurface investigation, should be presented to the contractor prior to the bid. Although the contract value of many mini-HDD projects may severely limit the possible geotechnical investigation, any available information about the site that can be gathered from the Soil Conservation Service, U.S. Geographic Survey, U.S. Army Corps of Engineers, etc., should be made known to the contractor. This information will allow the contractor to prepare a bid that is consistent with the probable soil conditions and can help to avoid possible claims.

3.6.5 Minimum qualifications

To ensure a safe, efficient, high-quality project, the owner should present a list of minimum qualifications to the potential contractors. These minimum qualifications typically include a minimum number of mini-HDD projects or footage successfully completed by the contractor. An emphasis should be placed on projects with conditions that closely match the project to be bid. The contractor should furnish a list of references where mini-HDD techniques were used in similar ground conditions. Requests for submittal of resumes of key staff and consultants may be appropriate, especially on large or difficult jobs. Financial data on the contractor and any subcontractors should also be furnished. The deadline for submittal of these qualifications should be clearly specified and should be prior to contract award.

3.6.6 Prequalification

There is much controversy over setting standards that must be met before a contractor is prequalified to bid a project. Arguments against prequalification include the potential for misuse and the impact on competition and costs. Some contractors are understandably wary of the practice. However, on complex or large projects in which emerging technologies are specified, prequalification procedures have been used to increase the probability of successful project completion and should be considered as a useful tool. On small, relatively simple projects, prequalification is unnecessary.

On projects where prequalification is considered necessary, the prequalification requirements should be carefully developed and enforced to ensure fairness to all participants. On private projects, the owner is free to set any prequalification standard desired. On projects involving the use of public funds, law may define the criteria for prequalification.

3.6.7 Minimum submittal requirements (from contractor to owner)

To ensure compliance with the requirements of the specifications, a number of submittals should be required from the contractor. The specifications should clearly state the minimum submittal requirements for the contractor. The timing of the various submittals should be in accordance with the submittal schedule as presented in the contract. Submittals detailing the construction process, equipment, drilling fluids, layout, and machinery setup should be approved by the engineer prior to construction. Other submittals (e.g., as-built construction records) will be submitted throughout the construction process.

3.6.8 Requirements for monitoring and protecting existing utilities and site features

Whenever the planned alignment is in close proximity to existing utilities, these utilities should be constantly monitored for displacement or damage. The contract documents should clearly state the monitoring requirements for such utilities. When necessary, the owner should specify the level of noise, lighting, traffic interruption, and work hours that will be acceptable during construction. In addition, if the contractor disturbs the surrounding environment, existing utilities, or structures, the contractor should be required to restore them to their original condition.

3.6.9 Measurement and payment

Ideally, the payment procedure should be fair and easily interpreted by the contractor and the owner. For small jobs or for a small component of larger projects, lump sum contracts are often preferred. However, for most mini-HDD projects, payment by the lineal foot of installed pipe is often preferable. Payment by the lineal foot allows the contractor to price each drive according to degree of difficulty, complexity of the site conditions, and anticipated competition. A combination of lump sum, lineal footage, or time and materials may be applicable when the specified project includes difficult ground conditions. For payment purposes, the length of installation may be defined as the distance along the product pipe line (e.g., in the case of curved bore paths or alignments). Short reaches of transition constructed by open cut may be paid at the same price as bid for mini-HDD installation or as a separate unit price.

3.6.10 Remedial action requirements

During the drilling operation, if any large obstruction is encountered that cannot be drilled through, the drill path may deviate significantly from the intended path or have to be abandoned, or the planned line may have to be relocated. In such cases, the contractor should inform the owner or the engineer and ask for direction. The bid documents should address such circumstances in an attempt to reduce claims against the owner. The contractor should be aware, prior to bid, how these problems will be handled, including information on payment (whether the owner will pay on a time and materials basis or on a lump sum basis, or whether the situation will be negotiated on a case-by-case basis).

When an underground utility is struck, in addition to the problems associated with the alignment of the new pipeline, there may be significant damage to the existing utility that may require repair. The contractor must immediately notify that utility owner of the location and nature of damage. Also, the contractor must allow the utility owner a reasonable time to accomplish necessary repairs before continuing the drilling. In general, when a correctly marked and specified utility line is struck and

damaged, the damage caused by the contractor will be repaired at his own expense. For damage to utility lines that are unmarked or incorrectly located, the owner would be responsible. The accuracy of utility locations and the required clear space should be specified in bid documents provided to bidders.

Most contract documents cannot or do not cover all the problems that may occur on a project. The owner and engineer should strive to identify anticipated problems and should establish or request submittals detailing a course of action for the contractor to follow in the event that problems are encountered. These actions should cover all anticipated problems.

3.6.11 Dispute resolution

Due to the nature of underground construction, problems may occur that are not covered in the contract. These problems may be due to unpredictable subsurface conditions, insufficient site investigations, or lack of experience with directional drilling technologies. As a result, directional drilling jobs may be vulnerable to disputes. To minimize claims, a fair dispute resolution plan may be useful on large or complex projects. If used, it should be incorporated into the contract and presented to the contractor. The dispute resolution plan should attempt to settle disputes in a fair and timely manner. These plans typically require both parties to submit to arbitration by a third party when the parties cannot resolve the dispute on their own. Dispute Resolution Boards (DRB) and mediation are additional methods sometimes used in settling disputes. These issues are described in more detail in *Pressure Pipeline Design for Water and Wastewater* (ASCE 1992).

3.7 Submittals from Contractor to Owner

3.7.1 General

Submittals requested by the owner from the contractor are critical to ensure compliance with the project specifications. In addition, they provide the basis for monitoring details of the project. These submittals, or portions of, can be provided at various points during the procurement and construction process. The submittals of interest include details on construction methods, project scheduling, qualification, certifications, quality control, construction records, and safety. Each of these items will be discussed in this section.

3.7.2 Construction methods and materials

The construction method submittals are a detailed explanation of the various steps involved in the construction process. They should include equipment, detailed by specific manufacturer's literature pertaining to the project; techniques, including a methodology statement detailing the operation of the equipment to ensure product pipe accuracy; materials, including certifications for pipe and drilling fluids; and other permanent and temporary construction site features. These submittals should include all details of the mini-HDD method including the type of locating system, the thrust, pullback, and torque capabilities of the machine, and details of the reaming and pullback operation.

3.7.3 Sequence of operation

The contractor should provide a sequence of construction operations corresponding to the various items reported in the Construction Methods submittal. For projects with multiple drilled crossings, estimated drilling and set-up times should be submitted to the owner. Unless local ordinances or unusual project requirements dictate otherwise, working hours should be left to the contractor's discretion and should not be restricted. Multiple shifts should be permitted, if noise levels do not exceed the maximum levels contained in local ordinances.

3.7.4 Site layout

Construction site layout information is important to the owner to verify that the operations do not infringe on personal property or unnecessarily interfere with any public or private operations. A sketch should be submitted indicating storage areas, equipment set-up areas, construction staging areas, and locations of all major supporting equipment.

3.7.5 Spoil disposal methods and locations

The mini-HDD process does not typically produce significant amounts of spoil or drilling fluid returns. However, this submittal should address the method of removing spoils from drilling fluid returns, equipment to remove the spoils from the site, disposal methods, and locations where the material will be disposed. This submittal should also include tests for potentially contaminated spoils as well as management and disposition of materials that are determined to be contaminated.

3.7.6 Contractor qualifications

The contractor must provide verification of qualifications to the owner. The number of references required by the owner should be furnished. References should have direct knowledge of the contractor's experiences on projects which include installation with the mini-HDD method. Complete names, affiliations, addresses, and telephone numbers should be furnished so the owner may contact the references to verify satisfactory performance. The contractor should furnish background information on key personnel to allow the owner to ensure the equipment operator and other key staff have adequate experience on similar projects with similar ground conditions. The contractor should provide documentation of at least the minimum amount of project experience required by the owner for drill rig operators and superintendents and all key personnel. Supporting financial data on the company should also be submitted to ensure that the contractor and pipe supplier will be available to support the product in the long term. Similar background information should also be supplied on all subcontracts.

3.7.7 Drilling fluids

The contractor should submit information on all proposed drilling fluids, additives, and other expendable materials planned for the project. Submittals should include MSDSs on each material along with a description of where the material will be used and its purpose in the construction process.

Construction records documenting the viscosity of the drilling fluids, as measured with the Marsh funnel; specific gravity of the drilling fluid; drilling fluid volume, as determined by the recorded average flow rates of the slurry; and recorded drilling fluid pressures should be submitted to the owner at regular intervals during the construction process.

3.7.8 Quality assurance/control plan

The contractor's submittals should clearly address how the specification requirements on quality control items will be satisfied. These should address the quality of materials, construction procedure, and performance testing of the finished product. The contractor should ensure that the performance of completed utility lines is satisfactory. The performance certification may require performance monitoring for a stated period of time after construction is completed.

Although verification of finished pipeline location is rare, due to excavation procedures necessary to establish actual location, it may be important to control deviations at intermediate points (between entry and exit locations) to minimize the potential of striking other utilities, and minimize the potential for encroachment into adjacent rows. If this is deemed necessary, the contractor should submit a plan for locating the actual position of each pipeline.

3.7.9 Documentation for as-built drawings

When the installation is completed, plan and profile information of the installed product pipe should be provided showing permanent references and other adjacent surface and subsurface features. The depth and position of the pipe as determined by the locator, at 5- or 10-ft-intervals (or other intervals, as specified by the engineer depending on length and complexity of the project) during the pilot hole boring operation, should be submitted for preparation of the as-built drawings. Any deviation from the designed plan and profile should be clearly presented in the drawings so that during any future drilling or other activity, the installed line can be accurately located and avoided. The engineer should approve the information submitted by the contractor for preparation of as-built drawings. In addition, potholes might be excavated at some critical locations to verify the depth and position of the installed pipe. Any unforeseen obstructions or other unusual circumstances encountered during the drilling process should be indicated. In general, the depth and position of the installed pipe measured by the locator may be considered as accurate within allowable tolerances, subject to independent verification that has been performed for that locator system, or spot checks as described previously.

3.7.10 Safety plan

The safety plan is critical to the construction operation to ensure that the public and workers are protected from construction hazards. This safety plan should include a submittal of the contractor's safety procedures for all workers and should emphasize electrical strike protection.

3.7.11 Construction records

Various submittals are required during the construction process to monitor the project. These include the following: preconstruction survey reports, documented as-built conditions, construction logs, materials installed, extent and causes of delays, locations of affected areas, and unusual

problems or conditions encountered. Records should include information on slurry viscosity, specific gravity, volume used, and pressures. In addition, machine thrust and torque should be submitted along with logs of the actual time required for the drilling and pullback operations.

4 Guidelines for Microtunneling

4.1 Introduction

4.1.1 Scope

This chapter addresses those issues related to the evaluation, selection, application, and performance of all operations required to install pipelines using microtunneling methods, including discussions on materials, labor, and equipment. The information presented is intended to help those who may be unfamiliar with trenchless technology and microtunneling. The focus is on the processes, equipment, and materials used, the applications, potential limitations, the problems that can be encountered, and successful approaches to overcoming problems. The information is not intended to be prescriptive, but rather informative. From this information, the engineer should obtain an understanding of the important issues and the resources available for addressing these issues. The information presented should allow the engineer to proceed with the design and development of specifications appropriate for particular project requirements and site conditions. Each project and each site has individual characteristics. The design and specifications must be tailored to those characteristics. The information presented is intended to span the range of conditions. However, highly complex projects or ground conditions require special consideration. The information presented in this chapter may be inappropriate for certain conditions; good judgment and caution are always appropriate.

4.1.2 Definition and range of applications

Microtunneling is a trenchless technology for construction of pipelines to close tolerances for line and grade. Applications are typically for gravity sewers, although other specialized projects have been constructed using this method. The method was developed in the 1970s in Japan, refined in Germany and the United Kingdom, and made its debut in the United States in 1984. By the end of 1993, over 250,000 linear feet of pipe had been installed by microtunneling methods (Norris, Bennett, and Iseley 1994). By September 1994, this figure had increased to over 300,000 ft (Norris, Bennett, and Iseley 1995).

No universally accepted definition of microtunneling exists, but it can be described as a remotely controlled, guided, pipe-jacking process that provides continuous support to the excavation face. The guidance system usually consists of a laser mounted in the jacking pit as a reference with a target mounted inside the articulated steering head of the microtunneling machine. The microtunneling process does not require personnel entry into the tunnel. The ability to control the stability of the

excavation face by applying mechanical or fluid pressure to the face to balance groundwater and earth pressures is a key element of microtunneling.

Although microtunneling was originally defined to be non-man-entry size (less than 900-mm diameter in Japan and less than 1,000-mm diam in Europe), it is worth noting that approximately 40 percent of the pipe installed by the microtunneling process as described above in the United States is larger that this diameter (Norris, Bennett, and Iseley 1994). Therefore, since the same type of system can be used to install almost any size pipe from 250-mm (10-in.) diameter to 3-m (10-ft) diameter or larger, no arbitrary size constraint should be placed on the definition. With proper selection, setup, and operation, microtunneling machines can be successfully used under a variety of conditions, ranging from soft soils to soft rock, both above and below the water table.

The microtunneling process is a cyclic pipe-jacking operation. The microtunneling machine is pushed into the earth by means of hydraulic jacks carefully mounted and aligned in the jacking shaft. As the jacks are fully extended, the machine is pushed out of the pit, and the jacks are then retracted. A product pipe or casing is then inserted between the jacking ring and the microtunneling machine or previously jacked pipe, necessary connections are made, and the pipe and machine are advanced another drive stroke. This cycle is repeated until the completion point (a reception shaft) is reached.

The jacking and reception shafts are significant cost components in microtunneling projects. Dimensions of each shaft are dependent on machine and jacking frame dimensions, pipe dimensions, and site conditions. Shaft dimensions typically range from 2.4 to 6 m (8 to 20 ft) in length or diameter for pipe lengths of 1.2 to 3 m (4 to 10 ft). Pipe lengths of 20 ft or larger have been used in cases where large shafts could be constructed. The goal is usually to use the minimum shaft size that will allow reasonable production rates and thereby minimize the cost associated with this component.

There are two primary types of microtunneling systems, auger and slurry, defined by the method of spoil removal. These operating systems differ in their degree of control of ground conditions at the face. The slurry system is generally capable of a more precise control. The slurry system can handle higher groundwater pressures and unstable ground conditions, but at the disadvantage of added mechanical complexity and cost. In addition, production rates may be slightly lower for slurry machines. Auger machines have limitations on the length and diameter of installed pipelines, due to the power requirements for turning the auger and head.

Both auger and slurry systems consist of five independent subsystems:

a. Mechanized excavation system.

b. Propulsion or jacking system.

c. Spoil removal system.

d. Guidance and control system.

e. Pipe lubrication system.

4.1.2.1 Mechanized excavation system

The mechanized excavation system is the cutterhead mounted on the face of the microtunnel boring machine and is powered by electric or hydraulic motors located in the machine. Cutting heads are available for a variety of soil conditions. Microtunneling machines have been successfully used on rock projects, and some manufacturers claim their machines can bore through rock with unconfined compressive strengths of up to 30,000 psi. However, improved cutters, bearings, and mounting assemblies, combined with an effective system for applying a high thrust to the face of the drive, are needed to significantly advance rock microtunneling capabilities. Most machines are designed with rock crushers in the heads to handle small boulders and other obstructions up to 30 percent of the diameter of the machine. The crushing mechanism is designed to reduce a boulder to particle sizes of 3/4 to 1 in. so that it can either be removed by an auger or by the slurry spoil removal system.

The boring machine also houses the articulating steering unit with steering jacks and the laser control target. Additional components which may be located in the microtunnel boring machines (depending on the type of machine) include the mixing chamber, pressure gauges, flow meters, and control valves.

Microtunneling machines have the capability of counterbalancing the earth pressure and the hydrostatic pressure independently of each other. The earth pressure is counterbalanced by careful control over the propulsion system and spoil removal system. This force must be carefully regulated to stay higher than the active earth pressure, but lower than the passive earth pressure so that subsidence and heave are minimized. The groundwater can be maintained at its original level by counterbalancing with slurry pressure or compressed air.

4.1.2.2 Propulsion or jacking system

As mentioned previously, the microtunneling process is a pipe-jacking process. The propulsion system for the microtunneling machine and the pipe string consists of a jacking frame and jacks in the drive shaft. The jacking units are specifically designed for the microtunneling process, offering compactness of design and high-thrust capacity. Capacity ranges from approximately 100 tons to well over 1,000 tons, depending on the length and diameter of the drive and the soil-jacking resistance that must be overcome. The soil resistance includes resistance from face pressure, resistance from friction and adhesion along the length of the steering head, and the pipe string. Existing methods for estimating jacking forces are based on drive length, average ground conditions, pipe characteristics and machine setup, and operating characteristics. A reliable estimate of the required jacking force is critical to ensure that the needed thrust capacity will be available and that the pipe will not be overloaded. For this estimate to be reliable, it requires a knowledge of pipe-loading conditions and machine-ground interaction that is difficult to obtain in many cases. Consequently, most jacking load estimates have been based on the "rule of thumb" experience (Lamb, Lys, and Garrett 1993). This approach is not always satisfactory; sometimes, pipe with a much higher or lower capacity than necessary may be specified. Alternate methods for predicting jacking forces are discussed in detail in Section 4.5.2.

The propulsion system provides two major pieces of information to the operator: the total force or hydraulic pressure that is being exerted by the propulsion system and the penetration rate of the pipe being pushed through the ground. The penetration rate and the total jacking pressure being generated and applied to the face are important for controlling the counterbalancing forces of the tunnel boring

machine to maintain safe limits. For example, if penetration rates are very high, yet torque is low, the stability of the face may be marginal.

4.1.2.3 Spoil removal system

Microtunneling spoil removal systems can be divided into the slurry transportation system and the auger transportation system. The operating systems differ in the degree of control of ground conditions at the face, with the slurry system generally being capable of more precise ground control. Both of these systems have been used extensively in this country and abroad. They have been successful when used under the appropriate conditions. In the slurry system, the spoil is actually mixed into the slurry in a chamber that is located behind the cutting head of the tunnel boring machine. It is hydraulically removed through the slurry discharge pipes, installed inside the product pipe. This material is then discharged into a separation system. The degree of sophistication of the spoil separation system should be based on the type of spoil that is being removed and project constraints, including slurry disposal requirements and costs. The effluent of the separation system is recirculated to become the charging slurry for the microtunneling system; thus, the system is designed as a closed-loop system.

Because the slurry chamber pressure is used to counterbalance the groundwater pressure, it is important that the velocity of the flow, as well as the pressure, be closely regulated and monitored. Regulation is accomplished by variable speed charging and discharging pumps, bypass piping, and control valves. As a result of this capability to counterbalance the hydrostatic head accurately, these machines have worked successfully in situations with high hydrostatic pressure (up to 70- to 100-ft heads). The machine can be completely sealed off from external water pressure, allowing underwater retrieval, which has been successfully accomplished on two recent projects at Corps of Engineers reservoirs (Crowder 1993).

The auger spoil removal system uses an independent auger system in an enclosed casing inside the product pipe for spoil removal. The spoil is augered to the drive shaft, collected in a skip, and then hoisted to a surface storage facility near the shaft. Typically, water may be added to the spoil in the machine to facilitate spoil removal. However, one of the advantages of the auger system is that the spoil does not have to reach pumping consistency for removal.

In general, slurry microtunneling machines are capable of more precise ground control because of the ability to balance groundwater and earth pressures with slurry face pressures, but at the disadvantage of added mechanical complexity and cost. In addition, production rates may be slightly slower for slurry machines. The auger machine does have recognized limitations with regard to ground control, especially if high groundwater levels and wet flowing sands or silts are encountered. In certain ground conditions, a skilled operator can maintain satisfactory ground control with proper auger machine setup. In addition, auger machines have limitations on the length and diameter of drives that can be installed, due to power requirements for rotating the auger and cutterhead. Intermediate jacking stations are not practical with auger machines because of the fixed-length auger casing sections.

If slurry handling and disposal is not addressed prior to construction, serious problems can arise, resulting in excessive costs or claims. When tunneling through soils with a high percentage of fines (i.e., particles finer than the #200 sieve), slurry separation can present a significant problem. Often fine material will not settle out by gravity, even when the slurry is allowed to sit for a considerable

length of time. The slurry then becomes "thick," and the contractor must use a fresh supply of slurry water in order for the tunneling operation to progress (thick slurry can cause abnormally high face pressures and does not allow for efficient muck transportation). Often mechanical separators, such as hydrocyclones, are necessary for slurry separation. Alternatively, the thick slurry may need to be trucked offsite to a proper disposal area.

When difficult ground conditions are expected, careful evaluation and selection of machine type, setup, and operation are essential. It is equally important to devise remedial action plans to be quickly implemented in the event that problems occur, such as slurry leakage, loss of ground, or stopped advancement of the machine.

4.1.2.4 Guidance system

The heart of most guidance systems is the laser, although other devices can be used. The laser provides the alignment and grade information for the machine to follow. The laser beam must have an unobstructed pathway from the drive shaft to the target located in the machine head. The laser must be supported in the jacking pit so that it is independent of any movement that may take place as a result of forces that are being created by the propulsion system. The target that receives the laser information can be an active or passive system. The passive system consists of a target grid mounted in the steering head that receives the light beam from the laser; this target is monitored by a closed-circuit television camera, also mounted inside the steering head. This information is then transferred back to the monitor screen on the operator's control panel in order to make any necessary steering corrections. The active system consists of photosensitive cells on the target that convert the information laser into digital data. Those data are electronically transmitted back to the control panel so that the operator is provided with a digital readout of the location where the laser beam is hitting the target. Both the active and passive systems have been used extensively and have been found to be reliable.

4.1.2.5 Control system

All microtunneling systems rely on remote-control capability, allowing operators to be located in a safe and comfortable control cabin immediately adjacent to the drive shaft, so the operator can visually monitor activities in the shaft. If the control cabin cannot be set up adjacent to the drive shaft due to space limitations, a CCTV system can be set up in the shaft to allow the operator to monitor activities using a television monitor. Control consoles are typically mounted in a standard container with 8- by 20-ft dimensions. However, consoles can be mounted in a variety of containers to suit tight space requirements. The operator's skills are a crucial ingredient to a successful project. The operator must monitor numerous bits of information continuously fed to the control panel; he must observe the work crew's activities and other site activities, evaluate this information, and make decisions on future actions. Information relayed back to the operator is audible, tactile, and visual, as sounds and vibrations generated in the microtunneling machine are transmitted to the operator. Other information that must be monitored includes: the line and grade of the machine, cutterhead torque, jacking thrust, steering pressures, slurry flow rates, pressures for slurry systems, and the rate of advancement.

The sophistication of control systems varies from totally manual to completely automatic. For the manual system, the operator evaluates all of the information and makes all necessary decisions regarding corrective actions. The operator is responsible for recording all information at appropriate

intervals during the pipe-jacking operation. All of the monitoring and recording of data is now automated on many machines with a computer that provides a printout on the condition of the various systems at selected time intervals. Systems exist that use fuzzy logic for making necessary corrections in the operational process (Kawakami 1992). This allows the machine to automatically acquire, evaluate, and compare the data to corrections that are typically used for that type of condition. The machine will then make those corrections. With this system, the operator monitors the actions to ensure that the automatic corrections are those that the operator thinks are appropriate. Manual override of the automatic corrections is also possible.

4.1.2.6 Pipe lubrication system

The pipe lubrication system consists of a mixing tank and necessary pumping equipment to transmit the lubricant from a reservoir near the shaft to the application points inside the machine or along the inside of the pipe. Pipe lubrication is optional, but recommended for most installations, particularly for lines of substantial length. The lubricant can be either a bentonite or polymer-based material. For pipe systems that are non-man-entry size (less than 36 in. in diameter), the most practical application point is in the machine shield. For sizes greater than a 36-in. diameter, man-entry is possible, and injection points can be installed at intervals throughout the pipe. These intermediate application points can be plugged and the supply lines removed upon completion of the drive. Lubrication can substantially reduce the total thrust required to jack the pipe.

4.1.3 Pipe materials

The types of pipe or conduit that can be installed include concrete, glass-fiber reinforced plastic (GFRP or Hobas), steel, and vitrified clay. Other types of composite material pipes have been used in Europe and may eventually enter the U.S. market.

4.1.4 Crew requirements and productivity

A highly skilled crew of four to eight is typically used, and production rates are approximately 30 to 60 ft/day for routine jobs, although rates of 200 ft/day or higher have been achieved. Mobilization time typically ranges from 3 to 8 days, and surface space requirements are minimal, so disturbance of the ground surface and disruption of surface activities are much less than for open-cut methods.

4.2 Applicable References

The development of standards of practice and standards for equipment and materials is in its infancy in the United States. The list of available references given below indicates some deficiencies that should be addressed. Furthermore, the listed references are nonuniform in their treatment of subjects from the plant and equipment required to the expendable and permanent materials.

4.2.1 American Society for Testing and Materials (ASTM):

(Unless otherwise noted, all ASTM Standards should be for the latest year of publication.)

4.2.1.1 Vitrified clay pipe

ASTM C 109	"Test method for hydrostatic infiltration and exfiltration testing of vitrified clay pipelines." *(Test Method)*
ASTM C 301	"Test methods for vitrified clay pipe." *(Test Method)*
ASTM C 828	"Test method for low-pressure air test of vitrified clay pipelines." *(Test Method)*
ASTM C 896	"Definition of terms relating to clay products." *(Definition)*
ASTM C 1208	"Standard specification for vitrified clay pipe and joints for use in jacking, slip-lining, and tunnels." *(Specification)*

4.2.1.2 Concrete pipe and materials

ASTM C 33	"Specifications for concrete materials." *(Specifications)*
ASTM C 76	"Reinforced concrete culvert, storm drain and sewer pipe." *(Specification)*
ASTM C 150	"Specifications for Portland cement." *(Specification)*
ASTM C 185	"Specifications for steel wire fabric, plain for concrete reinforcement pipe." *(Specification)*
ASTM C 361	"Reinforced concrete low-head pressure pipe." *(Specification)*
ASTM C 443	"Joint for circular concrete sewer and culvert pipe using rubber gaskets." *(Specification)*
ASTM C 497	"Standard methods of testing concrete pipe, manhole sections, or tile." *(Test Method)*
ASTM C 969	"Standard practice for infiltration and exfiltration acceptance testing of installed precast concrete sewer lines." *(Specification)*
ASTM C 1208	"Typical joint design." *(Specification)*

4.2.1.3 Centrifugally cast glass-fiber reinforced polyester resin pipe (GFRP or Hobas)

ASTM D 543	"Specification for test method for resistance of plastics to chemical agents." *(Specification)*
ASTM D 638	"Test method for tensile properties of plastic." *(Test Method)*
ASTM D 790	"Test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials." *(Test Method)*
ASTM D 2412	"Test method for determination of external loading characteristics of plastic pipe by parallel-plate loading." *(Test Method)*
ASTM D 3262	"Specifications for fiberglass (glass-fiber-reinforced thermosetting resin) sewer pipe." *(Specification)*
ASTM D 3681	"Test method for chemical resistance of fiberglass (glass-fiber-reinforced thermosetting resin) pipe in a deflected condition." *(Test Method)*
ASTM D 4161	"Specifications for fiberglass (glass-fiber-reinforced thermosetting resin) pipe joints using flexible elastomeric seals." *(Specification)*
ASTM F 477	"Specifications for elastomeric seals (gaskets) for joining plastic pipe." *(Specification)*

4.2.1.4 General

ASTM C 923	"Specification for resilient connectors between reinforced concrete manhole structures, pipes and laterals." *(Specification)*
ASTM C 936	"Infiltration testing." *(Test Method)*
ASTM D 471	"Specifications for test methods for rubber property-effect of liquids." *(Specification)*

4.2.1.5 Soil and rock

ASTM C 117	"Specific gravity computations." *(Test Method)*
ASTM D 317	"Water content by nuclear gage." *(Test Method)*
ASTM D 421	"Practice for dry preparation of soil samples for particle-size analysis and determination of soil constants." *(Specification)*
ASTM D 422	"Test method for particle-size analysis of soils." *(Test Method)*
ASTM D 653	"Terminology relating to soil, rock, and contained fluids." *(Definition)*

ASTM D 698	"Test methods for laboratory compaction characteristics of soil using standard effort (12,400 ft-lbf/ft^3 (600 kn - m/m^3))." *(Test Method)*
ASTM D 854	"Test method for specific gravity of soils." *(Test Method)*
ASTM D 1140	"Test method for amount of material in soils finer than the no. 200 (75-μm) sieve." *(Test Method)*
ASTM D 1556	"Test method for density and unit weight of soil in place by the sand-cone method." *(Test Method)*
ASTM D 1587	"Practice for thin-walled tube sampling of soils." *(Specification)*
ASTM D 1632	"Practice for making and curing soil-cement compression and flexure test specimens in the laboratory." *(Specification)*
ASTM D 2216	"Method for laboratory determination of water (moisture) content of soil, and rock." *(Test Method)*
ASTM D 2217	"Practice for wet preparation of soil samples for particle-size analysis and determination of soil constants." *(Specification)*
ASTM D 2435	"Test method for one-dimensional consolidation properties of soils." *(Test Method)*
ASTM D 2487	"Test method for classification of soils for engineering purposes." *(Test Method)*
ASTM D 2488	"Practice for description and identification of soils (visual-manual procedure)." *(Specification)*
ASTM D 2850	"Test method for unconsolidated, undrained compressive strength of cohesive soils in triaxial compression." *(Test Method)*
ASTM D 2922	"Test method for density of soil and soil-aggregate in place by nuclear methods (shallow depth)." *(Test Method)*
ASTM D 3080	"Test method for direct shear of soils under consolidated drained conditions." *(Test Method)*
ASTM D 3550	"Practice for ring-lined barrel sampling of soils." *(Specification)*
ASTM D 4221	"Test method for dispersive characteristics of clay soil by double hydrometer." *(Test Method)*
ASTM D 4318	"Test method for liquid limit, plastic limit, and plasticity index of soils." *(Test Method)*

ASTM D 4546 "Test methods for one-dimensional swell or settlement potential of cohesive soils." *(Test Method)*

ASTM D 4643 "Test method for determination of water (moisture) content of soil by microwave oven method." *(Test Method)*

ASTM D 4767 "Test method for consolidated undrained triaxial compression test on cohesive soils." *(Test Method)*

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4.3 Site Investigation

This section addresses site investigation issues that are important for microtunneling projects. The references given in Section 4.2 provide detailed guidance on conducting site investigations, laboratory and field testing, and interpretation and use of site investigation and test data for a wide range of projects and conditions. The focus in this section is on identification of the most important site characteristics for microtunneling, site investigation strategies and techniques for obtaining the information required, and application of this information to avoid or solve problems.

The site investigation requirements for microtunneling are no different in principle than for other subsurface excavation and tunneling projects. No new investigation methods must be developed for

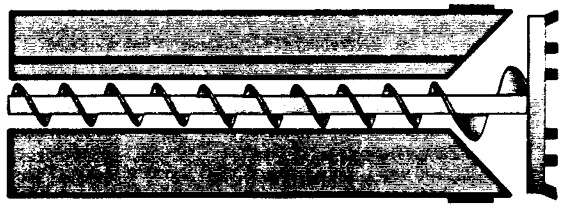
microtunneling projects; available tools are applicable to this technique. This statement does not imply that development of new tools or improvements are not needed in site investigation, especially advances that provide more reliable data, are less expensive, take less time, or are less intrusive. However, the subsurface information required can be obtained, interpreted, and applied to microtunneling with the use of existing technology.

4.3.1 Need for geotechnical investigations on microtunneling projects

Claims are often made that microtunneling can be used under a variety of ground conditions from soft soils to rock, including mixed face and boulder ground, above or below the water table. The statement is true, but requires qualification. Microtunneling methods can be used under a wide range of conditions, and machines can be selected, set up, and operated by highly skilled crews to provide satisfactory results under these conditions. However, a given combination of machine, setup, and operating practice cannot be expected to perform at top efficiency under all possible ground conditions.

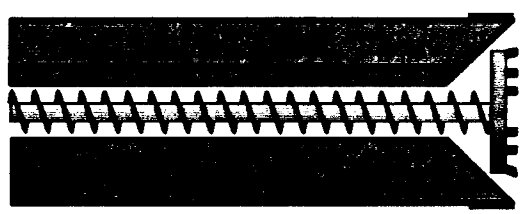
The need for machine adaptation has been demonstrated numerous times and places as exemplified by the field trials and developments that took place in the United Kingdom in the mid-1980s. (Nicholas and Robinson 1988; Washbourne 1993). In these trials, auger microtunneling machines that were originally designed for sandy soils with tight auger pitch were adjusted for use in heavy clays by decreasing the pitch of the auger blade. Opening sizes in the cutter wheel were also increased to allow heavy clay masses to enter the machine. Figure 4-1 illustrates different auger machine setups for clay and sand. Additional tests, such as those recently conducted at the WES facility, also exhibited the need for machine modifications in differing soil types (Bennett and Taylor 1993; Bennett, Khan, and Iseley 1994). In these tests, auger and slurry machines were tested in six different soil types to determine machine/soil interaction and machine performance. The auger machine cutter wheel had to be modified prior to the test to be able to cope with the various ground conditions. The modifications were reasonably successful considering the highly variable conditions and the necessary compromises. It should be noted that ground conditions do not generally vary over such a wide range on commercial projects, as they did at the WES test bed. The important point is that predominant ground conditions and their range of variability must be reliably established so the project can be designed, the specifications prepared, and the job bid. The soil conditions must also be known so that the proper machine can be selected, set up, and operated correctly. The potential range and likelihood of ground conditions that can adversely impact the performance of the machine must be identified, and the range of potential adverse effects that the machine may have on the ground and surrounding site features must be determined.

In the case of microtunneling, most projects are relatively small. On typical projects, 1 to 5 percent of the total contract value is budgeted for the geotechnical investigation. To put things into perspective, if a given project is estimated at $2 million, the geotechnical investigation might be budgeted for no more than $50,000 to $100,000. Therefore, available funding limits the extent of the geotechnical investigation. However, complex projects deserve and are sometimes allocated greater resources. The practical significance is that, in spite of all of the recommendations by the U.S. National Committee on Tunneling Technology (1984) and others for recognizing the critical importance of adequate funding for geotechnical investigations, the emphasis placed on geotechnical investigations is not likely to change soon or significantly.



Auger Machine Setup for Clay

- Cutter Disk Forward of Shield
- Oversize Auger (1st flight) to Clean Behind Cutter Disk
- Coarse Pitch on Auger Flights
- Large Openings in Cutter Disk



Auger Machine Setup for Sand

- Smaller Cutter Disk Recessed into Shield
- Tighter Pitch on Auger Flights
- Smaller Openings in Cutter Disk
- May Use Compressed Air at Face to Stabilize Wet Soils by Drying Wedge of Soil Between Disk and Shield

Figure 4-1. Auger setup for clay and sand

With these factors in mind, the following paragraphs are intended to summarize the most important issues that must be addressed during site investigations for microtunneling projects. Current practice is summarized for normal projects, with some recommendations made for making effective use of available information and correlations based on relatively low-cost indirect methods and index tests. Experience and good judgment are critical ingredients throughout the process and cannot be overemphasized.

4.3.2 Boreholes

New boreholes provide the basis for confirmation of inferences and preliminary conclusions drawn from study of regional and site geology, geophysical surveys, and analysis of logs of nearby borings and wells from previous projects. A wealth of information is available only from boreholes, including the undisturbed samples required for reliable characterization of important site features. One drawback is that boreholes provide information only along a single depth line. Relatively close spacing of boreholes is required, especially at complex sites, to obtain adequate information to allow development of accurate cross sections. Boreholes must be strategically placed to get the most valuable information at the most critical locations. Therefore, boreholes should be located at all shaft locations and at intermediate points no greater than 300 ft apart. Closer spacing of boreholes is appropriate in highly variable ground conditions, especially in mixed face conditions. Boreholes at shaft locations should be extended beyond the floor elevation by at least the maximum width of the shaft to allow evaluation of floor heave potential. Intermediate boreholes on the alignment should extend two tunnel diameters below the invert in case changes in design depth or grade are necessary.

Boreholes provide the most reliable indication of conditions to be encountered if they are located along the proposed centerline of the tunnel. However, some prefer to locate boreholes some distance off the centerline, to minimize the potential for loss of slurry through the borehole as the tunnel passes that location. If boreholes are located along the centerline, they must be properly abandoned, by tremie grouting with a bentonite cement grout mixture, to eliminate this potential problem. Boreholes that are to be converted to piezometers or wells must be located off-line.

4.3.2.1 Boring logs

Good boring logs are vital for correct interpretation of ground conditions. Geotechnical engineers learn to look for clues on boring logs that help them determine the adequacy and reliability of the information presented. An example of a good boring log is shown in Figure 4-2. From logs such as this, far more than the variability of soil type with depth can be determined.

The heading information should include complete details of the drilling operation, including date; project title; drilling company, drillers' and inspectors' names; type of rig and tools used; project location; borehole location, number, and ground surface elevation; and total depth of borehole. Sampling methods should be noted. On the sample, this is done using a legend, keyed to sample depths. The log itself should show elevation and depth, with strata boundaries and field classifications. The example log shows the number of blows per 6-in. sample penetration for all intervals where standard penetration testing was used, along with percent sample recovery in the split-spoon sampling device. Blow counts and recovery data provide important clues about whether appropriate care and methods have been used, in addition to the required information on consistency that is needed for a variety of uses, including evaluation of excavatability and settlement. The log also shows intervals where push-tube sampling was conducted. Push-tube samples are required for

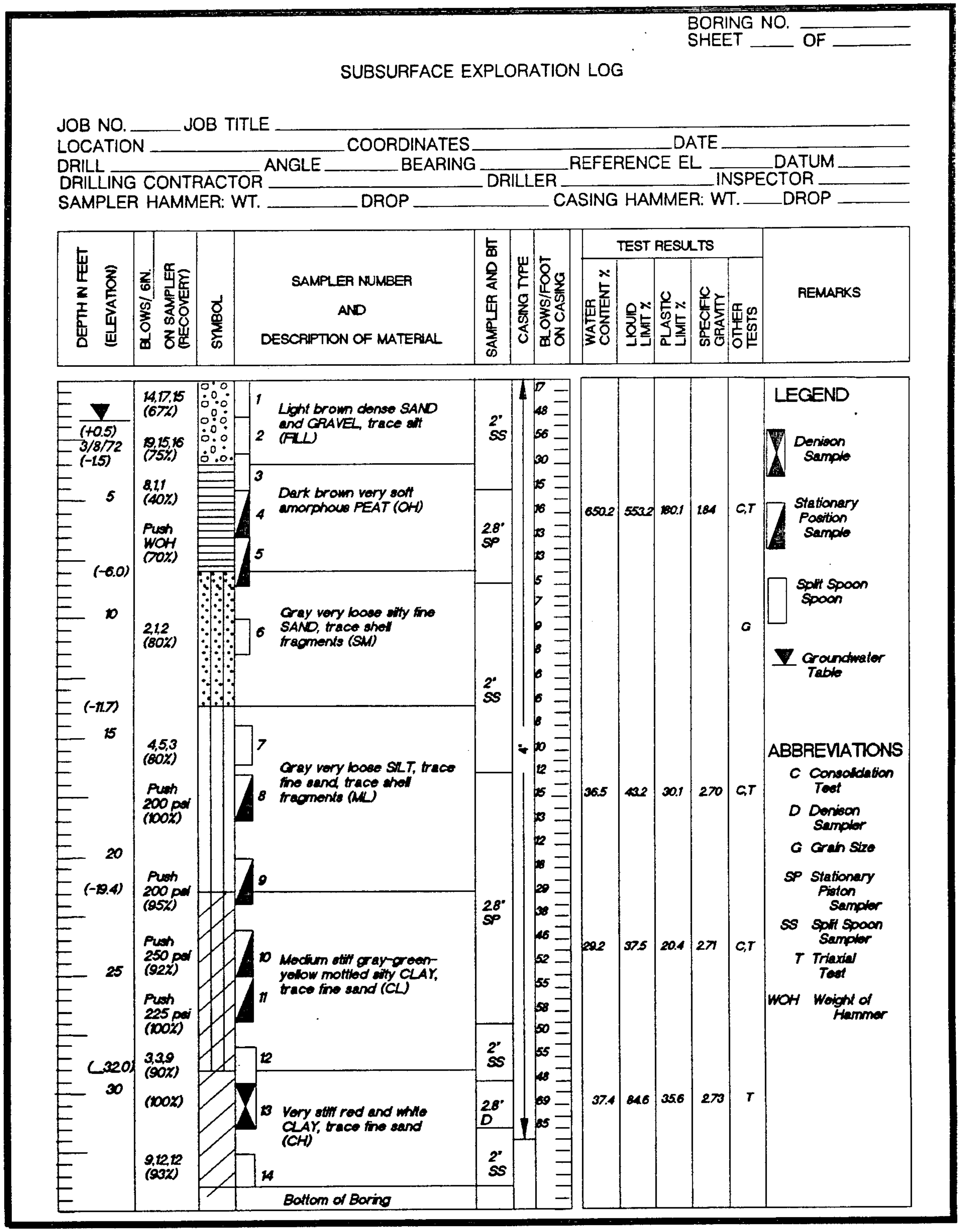


Figure 4-2. Example of boring log

laboratory tests on undisturbed samples of cohesive soils; the split-spoon samples are useful for classification, Atterberg Limits, water contents, and other tests that do not require undisturbed samples. Sample intervals and sampling methods should be shown, along with casing size and blows per foot or the casing, if used. Laboratory test results should be recorded at the depth intervals corresponding to the samples tested. Important observations should be noted in the remarks section.

A few cautionary notes are offered with regard to interpreting boring logs. Occasionally, boring logs show very high blow count materials (70 to 100 blows per foot) with relatively low recoveries, with the materials field classified as sand, silt, or gravel. The user of this information should be alert to the possibility that such high blow count materials may be misclassified because improper sampling methods were used. The probability of incorrect classification increases for recoveries less than 70 percent or so. Such materials should be sampled using rock coring methods. If proper sampling methods are used, such materials would, in many cases, be classified as weak rock, rather than soil. For microtunneling, the implications of such an error are very serious with regard to excavatability. In addition, any time that low recoveries are recorded, the user should question the reliability of reported classifications, stratifications, and engineering characteristics. Very often, the most important materials with respect to controlling engineering behavior are the materials not recovered. In addition, field classification often fails to properly distinguish between silts and clays. Erroneously classifying silt as a clay can lead to surprises with respect to potential loss of strength or bearing under repetitive loading, such as behind the thrust wall.

4.3.2.2 Indirect methods, index tests, and correlations

Site investigations are usually conducted on tight schedules and budgets. Therefore, maximum effective use should be made of relatively low-cost indirect methods, index tests, and correlations. However, use of such tools requires experience and good judgment to avoid misinterpretation.

Geophysical surveys, especially surface and downhole and cross-hole refraction methods, can be very helpful in establishing groundwater depth, top of rock, and distinct changes in stratification. Geophysical methods are also useful in planning borehole locations. Dip of rock strata can also be established if shots are made at both ends of a line of geophones. Other geophysical methods that may provide useful information under the right circumstances include acoustic subbottom profiling for projects to be constructed under bodies of water and ground penetrating radar for sites where sands, gravels, and rock are predominant geologic materials. Use of ground-penetrating radar may be inappropriate in clay soils and where salt water occupies soil pore space. Detailed discussions, including applications, limitations, and interpretation of geophysical methods are provided in EM 1110-1-1802 (U.S. Army Corps of Engineers 1979).

A variety of relatively inexpensive index tests can be used to supplement more expensive, time-consuming tests. Correlations with engineering properties of importance have been developed for many such tests and applications. The degree of reliability of such correlations is good in some cases, suspect in others. Due to the potential for misapplication, or extension to conditions beyond which a particular correlation was developed, advice should be sought from experienced geotechnical engineers when attempting to use correlations from index tests. However, these tools are useful and should not be overlooked. Particularly, valuable examples of index tests and correlations include those for correlating cone penetrometer resistance and standard penetration test blow counts with density, consistency, and undrained shear strengths; vane shear, Tor vane, and pocket penetrometer

tests with undrained shear strengths; grain-size analysis with permeability; and point load index with unconfined compressive strength of rock.

4.3.3 Important site characteristics

Site characteristics that should be determined for microtunneling projects are listed in the following. The potential impacts these characteristics exert on construction and the impacts that construction may have on site features are summarized. Methods for obtaining the data required are also described. The relative importance of individual characteristics will vary from project to project, and no particular significance should be placed on the order in which they are listed and discussed. Important site characteristics include:

a. Groundwater.

b. Obstructions.

c. Rock.

d. Difficult ground conditions.

e. Contaminated groundwater or soil.

f. Existing utilities, building foundations, and environmentally sensitive features.

4.3.3.1 Groundwater

Depth to groundwater should be confirmed by observation wells/piezometers at all shaft locations and at intermediate points for drives longer than 300 ft or where variable site conditions exist. Geophysical refraction surveys, existing borings, and wells are useful and cost effective for determining groundwater depth during the preliminary investigation, but should be supplemented with new observation wells/piezometers prior to design and construction. Field permeability tests and pump tests conducted at these locations can often clarify the degree of interconnectedness of sand zones and whether or not the wet sand zone is of limited extent (e.g., perched water). Observation wells/piezometers not only provide information on preconstruction groundwater levels, but also can be used to determine if groundwater levels are being lowered during construction. Lowered groundwater levels for extended periods of time can result in consolidation settlements of certain soil types (e.g., soft clays) and may adversely impact building foundations (e.g., wooden piles). For pipelines to be installed below groundwater using microtunneling, it is necessary to control groundwater levels near shaft locations to allow shaft construction and launch of the machine. Groundwater may be temporarily lowered by pumping or controlled by grouting the zone around shaft walls, especially in the areas near the entry and exit seals. In cases with high groundwater pressures, caissons may be sunk in place, and ground freezing may be appropriate in extreme cases, but this is an expensive control measure.

4.3.3.2 Obstructions

Obstructions are defined as objects or features that lie completely or partially within the cross-sectional areas of the planned pipeline excavation and that prevent continued forward progress of the

microtunneling machine. In general, when obstructions are encountered, the face must be exposed to allow removal. Access to the face may be gained by sinking a rescue shaft at the face, by sinking a shaft off-line and hand mining to the face, or by hand-mining from the reception shaft. Occasionally, a stuck machine can be freed by manipulation of the auger or slurry discharge system or counter rotation of the head. These measures should always be attempted before proceeding to expose the head. Shafts are expensive, as is machine downtime, so encountering obstructions is an expensive problem that delays project completion. It is therefore imperative to develop plans for dealing with obstructions, physically and contractually, before they are encountered. Most machine manufacturers claim their machines can deal with encountered nonmetallic objects that are less than one-third the size of the face. For an object to be successfully handled, it must be brought into the machine through the openings in the cutterhead and pulverized by the crusher mechanism. Cutterheads vary from completely open-faced to those with quite restricted openings. Trade-offs on selection of the most appropriate cutterhead design include the anticipated nature of the overall ground conditions, along with the nature, frequency, and estimated sizes of buried objects. For example, if no obstructions larger than approximately one-third the diameter of the machine are expected to be encountered and the objects are able to be crushed, relatively open-face machines might be appropriate. If frequent boulders, unreinforced concrete, or other buried hard objects larger than one third of the diameter are expected, a closed-face design with rock cutters or a combination of cutters mounted on the face may be more suitable. This design allows the larger objects to be cut and broken into digestible pieces before they enter the crusher. Advance rates are generally slower with closed-face designs, but less likelihood exists for stalling the machine. Open-face machines cannot handle large obstructions; these may become stuck between the cutter assembly and crusher, stall the machine, or rotate with the cutter assembly, advancing for some distance with the machine. This condition can lead to ground disturbances around the shield and resulting settlements.

Isolated wooden piles, timbers, shoring, bricks, and nonmetallic construction debris can usually be excavated by the machine, but advance rates are likely to suffer when such objects are encountered. Such objects may be expected in many urban congested areas, especially where the planned pipeline is sited in a shallow fill.

The likelihood of buried objects, their nature and relative sizes, should be established by the site investigation. This task requires evaluation of information from a variety of sources including regional and site geology reports, geophysical surveys, borings, and test pits. Regional and site geology reports and land-use records help to establish the likelihood and nature of buried objects. Geophysical surveys, borings, and test pits add detail and serve to verify preliminary conclusions drawn from these sources.

Geophysical surveys can sometimes provide insight on the relative sizes, frequency of occurrence, and locations of anomalies, depending on the depth of interest and resolution. Indications of anomalies, based on geophysical surveys and other information, should be verified with borings and test pits. Borings and test pits provide physical evidence of the nature, location, frequency, and size of buried objects at discrete sampling points. A carefully executed site investigation that uses all available tools effectively can provide reliable estimates of the nature, relative sizes, and frequencies of buried objects that may be encountered. However, actual locations and sizes may not be determined within practical budget and time constraints for site investigations. Again, this situation emphasizes the need to develop plans for dealing with obstructions, technically and contractually, before construction begins.

4.3.3.3 Rock

Claims have been made that microtunneling machines can be used in rock with unconfined compressive (UC) strengths of up to 30,000 psi. Advances are being made in rock cutting that are encouraging, but rock currently presents significant challenges to construction with microtunneling. The challenges include the need to apply high thrust loads to the rock face, so the cutters can cause the rock to spall, and the need for high thrust capacity cutters with bearing and mounting assemblies that are small enough to be fitted to a small-diameter machine head. On larger TBMs, large-diameter, high-capacity single disc cutters have proven effective for excavating very hard rock (UC > 45,000 psi). These disc cutters are up to 17 in. in diameter to provide required thrust-bearing capacity. The mounting blocks are correspondingly large. For small-diameter microtunneling machines, there simply is not enough space to mount large discs at the required close radial spacing to efficiently cut rock. A range of solutions have been attempted with varying degrees of success, from using ganged, multidisc cutters to strawberry, button-bit cutters or combinations. Small-diameter (5- to 7-in.) single-disc cutters have been developed and proposed for use on microtunneling machines. While preliminary laboratory test results appear promising (Friant 1994; Ozdemir 1995), field performance has not yet been established.

With these limitations in mind, site-investigation strategy should focus on determining the depth and extent of rock, rock type, rock quality (weathering, jointing, and fracturing), hardness, stress state, strengths, and abrasiveness. For clay shales, slake durability and swelling tendencies may be important and should be determined. Reliable exploration and test methods are available for determining these characteristics. Drilling and sampling procedures that ensure high core recovery rates and minimize damage to the core are essential. On rock projects, the material that is not recovered is often the most important for evaluating technical feasibility. Unconfined or triaxial compressive and tensile strengths, together with abrasiveness and in situ stresses, are key parameters for estimating excavatability. It should be noted that confining stresses exert significant influence on excavatability. Rock that may be easily cut with low thrust and torque, at or near the surface, becomes much more difficult to excavate with increasing depths, as average confining stresses increase at approximately 0.5 to 1.0 psi per foot of depth. Triaxial compression and extension tests are useful for evaluating confinement effects. Point load index tests and Schmidt hammer tests can be used to supplement unconfined compressive and triaxial tests and to obtain preliminary data.

The depth and areal extent of rock can be established with borings that are strategically located to supplement other site data, e.g., geophysical refraction, regional and site geology reports and maps, and logs of existing wells and boreholes. Abrasiveness is important for evaluating cutter service life and wear on other components, such as slurry pump impellers. Abrasiveness can be estimated using the Taber Abrasion and Shore Sclerescope tests.

Weathering, fracturing, jointing, and overall rock mass quality are important for estimating excavatability. This information, coupled with field permeability testing, could be useful for estimating potential slurry losses that may occur through open fractures and joints. Estimation of individual block sizes can be an important factor for evaluating the potential for blocks to become wedged in the cutterhead or to become separated or dislodged above the pipe and cause gouging of the pipe or couplings. RQD is widely used as an indicator of overall rock quality. Rock quality determinations can be refined, if necessary, using various rock mass classification schemes developed for construction of larger tunnels (Bieniawski 1979; Barton, Lein, and Lunde 1974).

4.3.3.4 Difficult ground conditions

The soft ground conditions that are most troublesome for microtunneling are essentially the same as those for larger, conventionally excavated tunnels. Raveling, flowing or running ground, squeezing ground, swelling ground, and mixed-face conditions present challenges to successful applications. The potential for these conditions must be determined to allow proper selection, setup, and operation of the machine. These conditions, along with groundwater conditions, establish the basis for selection of auger or slurry machines, design of the cutterhead assembly, selection of cutters for the head assembly, selection of overcut and lubrication, slurry characteristics, slurry separation equipment, auger pitch, and other important decisions.

The Tunnelman's Ground Classification, first described by Terzaghi (1950) and slightly refined by Heuer (1976), is useful for identifying these problem soil conditions as they relate to conventionally excavated, larger diameter tunnels. Descriptions of these soil conditions and their impacts on microtunneling are discussed in the following sections.

4.3.3.4.1 *Raveling ground conditions.* In conventionally excavated, large-diameter tunnels, chunks or flakes of material begin to drop out of the arch or walls sometime after the ground has been exposed, due to loosening or to overstress and "brittle" fractures (ground separates or breaks along distinct surfaces, opposed to squeezing ground). In microtunneling applications, raveling may cause chunks of material to cave onto the pipe wall or come into the face of the machine. Along the pipe wall, this effect can increase jacking loads by reducing the effects of lubrication and overcut. Raveling soils may threaten face stability, especially at the entry and exit shafts, where face pressures may not be carefully regulated. In fast raveling ground, the process starts within a few minutes; otherwise, the ground raveling is slow. Residual soils or sands with small amounts of binder may be fast raveling below the water table, slow raveling above. Stiff-fissured clays may be slow or fast raveling, depending upon degree of overstress. Site investigation data needed for identifying raveling ground include sieve analysis, undrained shear strength tests, standard penetration tests, stress states, and groundwater elevations.

4.3.3.4.2 *Running ground.* Granular materials without cohesion are unstable at a slope greater than their angle of repose. When exposed at steeper slopes, they run like granulated sugar or dune sand until the slope flattens to the angle of repose. Clean, dry granular materials are typically classified as running ground. Apparent cohesion in moist sand, or weak cementation in any granular soil, may allow the material to stand for a brief period of raveling before it breaks down and runs. Such behavior is called cohesive running. The main effect of running ground on microtunneling is the potential instability of the soil at the shafts, at the face of the machine, and on the overcut. The overcut will not stay open, making lubrication ineffective and increasing the jacking force. In addition, it is critical to maintain proper face pressure and slurry viscosity to prevent material from running into the face of the machine that results in settlement. Site investigation data for determining running ground conditions include sieve analysis and tests to determine soil classification.

4.3.3.4.3 *Flowing ground.* In a conventionally excavated, large-diameter tunnel, a mixture of soil and water flows into the tunnel like a viscous fluid. The material can enter the tunnel from invert as well as from the face, crown, and walls and can flow for great distances, completely filling the tunnel in some cases. In microtunneling, soil will not flow into the tunnel because of the continuous pipe

wall. However, the concerns in flowing ground are similar to those experienced in running ground where stability of the shaft, the face, and the overcut are difficult to maintain. Higher friction forces should be expected due to poor distribution of lubrication materials. Again, extreme caution should be employed by the operator to maintain proper face pressures and slurry viscosities. Stabilization of the soils around the shaft will be required. Typical soils that exhibit these properties include silt, sand, or gravel below the water table without enough clay content to give significant cohesion and plasticity.

Ground flow may also occur in highly sensitive clay when such material is disturbed. Sensitive clays are those soils with lower strengths in remolded condition, compared to undisturbed conditions. Soil sensitivity (S_t) is defined as the ratio of undisturbed to remolded undrained shear strengths, $S_t = S_u$ undisturbed/ S_u remolded. Information needed to determine the potential for flowing ground would include sieve analysis, Atterberg Limits, natural moisture content, sensitivity of clays, vane shear tests, and SPT on undisturbed and remolded specimens.

4.3.3.4.4 *Squeezing ground.* In conventionally excavated, large-diameter tunnels, ground squeezes or extrudes plastically into the tunnel without visible fracturing or loss of continuity and without perceptible increase in water content. In microtunneling applications, squeezing ground exerts force on the shaft supports and pipeline and can dramatically increase the normal force on the pipe wall. This in turn can increase jacking forces and in some cases can stop progress of the tunnel machine. As with flowing ground, stabilization of the soil around the shaft is required.

The nature of squeezing is a ductile, plastic yield and flow due to overstress, typically in ground with low frictional strength. Rate of squeeze depends on degree of overstress. Squeezing can occur at shallow-to-medium depth in clay of very soft-to-medium consistency. Stiff-to-hard clay under high overburden stresses may move into the excavation through a combination of raveling at the excavation surface and squeezing at some distance behind the free surface. Typical tests and information used for determining squeezing properties include undrained shear strength, consolidation test, SPT, and stress state.

4.3.3.4.5 *Swelling ground.* Ground absorbs water, increases in volume, and in the case of conventionally excavated, large-diameter tunnels, expands slowly into the tunnel. In microtunneling, the swelling pressure exerted on the pipeline increases jacking forces. In addition, the shaft floor slab may heave due to a combination of stress release and access to water. Line and grade control could suffer, and misalignment of the jacking frame could lead to eccentric loads on the pipe. Swelling soils include highly preconsolidated clay with plasticity (PI) index in excess of about 30, generally containing significant percentages of montmorillonite. When these soils are identified, it is critical to have a large overcut to avoid binding of the pipe string. In addition, it is not advisable to use clear water in the slurry make-up tank. Polymers and bentonite reduce the loss of water into the clay, which has a high affinity for adsorption. Site investigation data that are useful for evaluating swelling potential include soil classification, Atterberg Limits, clay mineralogy, soil suction, and consolidation tests. Table 4-1 relates swelling potential of soils to Atterberg Limits and soil suction test results.

Table 4-1
Swelling Potential of Soils Based on Index Properties and Suction[1]

Classification of Potential Swell	Potential Swell[2] Percent	Liquid Limit, LL Percent	Plasticity Index, PI Percent	Natural Soil Suction[3] tsf
Low	< 0.5	< 50	< 25	< 1.5
Medium	0.5 - 1.5	50 - 60	25 - 35	1.5 - 4.0
High	> 1.5	> 60	> 35	> 4.0

1 U.S. Department of the Army (1993).
2 Percent increase in the vertical dimensions of the soil layer.
3 Matrix soil suction measured without confining pressure, except atmospheric pressure.

4.3.3.4.6 *Mixed-face conditions.* Mixed-face conditions can present challenges to alignment, grade control, and stability of the face. Mixed-face conditions are defined by distinct variations in material properties and behavior within the cross-sectional area of the face, such as rock overlain by soft ground. Geophysical surveys complemented with borings can provide reliable indications of the top of the rock or hard layers. In the event that mixed-face conditions are identified, the cutter-head assembly can be designed to counteract adverse steering effects caused by the mixed-soil interface. The profile of the wheel should be aggressive and designed to excavate the harder formation. The operator must be acutely aware when the interface is encountered as the machine will have the tendency to ride the slope of the harder material. If the cutterhead is properly designed, the aggressive profile will "bite" into the harder material and cause the machine to dive into the harder material (the cutter bits not embedded in the harder material will tend to progress through the soft soil more quickly than those in the hard material). The operator must then counteract this diving response with appropriate steering. This crucial interface demands an experienced, alert operator; otherwise, steering control and stability control may be difficult. Because of the serious potential for line and grade deviations and stability problems, the planned pipeline depth should be adjusted to avoid mixed-face conditions, if at all possible.

4.3.3.5 Contaminated groundwater or soil

The presence of contaminated groundwater or soil can dramatically increase the cost of a project depending on the types of contaminants identified and the extent of contamination. The potential for contaminants must be identified during the site investigation, prior to construction, to avoid substantial increases in contract amounts due to changed conditions.

Proper soil and groundwater sampling and handling procedures should be followed during test drilling to ensure accurate results, especially if volatile organic compounds are anticipated. The site investigation should be extensive in areas of potential contamination, e.g., areas near gas stations, chemical plants, or buried fuel tanks. Contaminated zones should be delineated and presented in the contract. All information on the types and levels of contamination should be presented to the

contractor prior to bid. In addition, requirements for handling of contaminated soil and groundwater should also be presented to ensure the contractor complies with all local, State, and Federal laws. These recommendations should include testing requirements, provisions for soil storage/testing areas, methods for groundwater treatment and storage, and provisions for encountering contaminants in areas not in delineated contamination zones. In addition, the minimum concentration of identified contaminants that requires treatment should be specified. This will serve to avoid conflicts and delays when deciding whether a specific concentration of contaminant requires treatment.

If onsite treatment of contaminated soil and groundwater is required, special provisions should be made to establish contaminated work zones where the contractor can perform this task. Depending on the types of contaminants, the contractor may be required to use special safety provisions, and all onsite personnel may be required to have hazardous-material training. Both of these provisions are costly and should be determined before bid to avoid delays and increased costs.

4.3.3.6 Existing utilities, building foundations, environmentally sensitive features

Existing site features that could be damaged by the construction or that may impact the construction must be located or marked during the site investigation. Existing utilities may be located from as-built records, although locations of abandoned utilities are often not known. "Potholes," which are auger- or vacuum-extraction borings excavated for investigation purposes, should be used to confirm and mark locations of utilities that are near or intersected by the planned pipeline. Historic buildings usually require evaluation on a case-by-case basis to ensure protection, as is the case for environmentally sensitive areas.

4.4 Design Considerations

4.4.1 General

Critical design issues that must be properly addressed for successful microtunneling projects are discussed in this section. The issues, their relevance, and guidance for their disposition are presented. This discussion is intended to be informative, not prescriptive. As is true in all aspects of design and construction, caution, experience, and good judgment are vital ingredients.

4.4.2 Conditions that favor selection of microtunneling

4.4.2.1 Depths

Microtunneling can be used for pipe installation over a wide range of depths and is often cost-effective when the depth of cover is greater than or equal to 15 ft, due to the high cost of shoring a deep open-cut excavation. Microtunneling methods may also be cost effective at shallower depths if high levels of groundwater are present and existing utilities need to be relocated to facilitate cut-and-cover construction. In these cases, the cost of dewatering the excavation, combined with the open-cut shoring, utility relocation, and excavation costs, often exceeds the cost of microtunneling where only localized dewatering is required. However, sufficient cover is needed above the pipe crown to minimize the likelihood of heave of the surface and the potential for slurry migration to the surface.

In general, the ratio of depth to crown (h) to diameter (d) should be $h/d \geq 3$. In clay soils, projects may be feasible at shallower depths with auger or slurry machines, and in sand, with auger machines.

4.4.2.2 Environmentally sensitive/congested areas

Microtunneling methods can be especially appropriate in highly developed areas to limit the adverse impact of new construction. These impacts include traffic and business disruption, limited access, road closures, dust control, and increased noise levels. In addition, open-cut construction may not be feasible in congested areas as the new pipelines may be routed under existing structures. Microtunneling may be favorable if dewatering, required for open-cut excavations, threatens foundation stability of structures in the vicinity of the open-cut excavation.

4.4.2.3 Marginally stable or unstable ground conditions

In marginally stable or unstable ground conditions, shoring may be extremely difficult. In these situations, microtunneling may be favored for pipe installation to limit the amount of shoring that is necessary. Microtunneling can be successfully used in unstable ground conditions if the system is properly selected, set up, and operated.

4.4.2.4 Construction below the water table

Microtunneling machines with slurry soil conveyance systems are capable of operating below the groundwater table. In these situations, a mechanical seal, usually composed of a rubber flange, is attached to the wall of the drive and reception shafts. The flange seal is distended by the tunnel boring machine as it passes through. The machine then operates by creating a pressure balance at the head. This pressure is controlled and regulated by the operator from a remote console. The operator interprets readings from impulse transmitters and pressure gauges and balances pressure in the slurry inflow and outflow lines. With the slurry activated, the machine can advance while achieving an earth pressure balance.

This pressure balance allows pipe installation while controlling settlement or heave within specified tolerances. Typically dewatering is only required at the entrance and exit shaft locations, and all pipe installation can take place without dewatering along the length of the pipeline. This feature of slurry machines can make microtunneling extremely cost effective in areas with high groundwater levels.

When a pipeline is to be installed below groundwater levels, slurry machines generally allow more precise ground control because of their ability to balance groundwater pressures with slurry pressures. However, with proper machine configuration and operation, auger machines can maintain satisfactory control under low groundwater heads. Auger machines have recognized limitations with regards to ground control, especially if the machine encounters wet flowing sands and silts or high groundwater levels. When difficult ground conditions are expected, advice should be sought from machine manufacturers, experienced machine operators, or other experienced persons to ensure a properly equipped system capable of maintaining adequate ground control.

4.4.2.5 High accuracy requirements

When line and grade tolerances are critical, microtunneling methods can be very effective. Microtunneling machines are capable of steering an articulated shield to maintain line and grade

accuracy. Deviation from planned line and grade is monitored, usually by a laser mounted in the drive shaft. The laser target system is located in the head assembly, and the laser beam is projected onto the target from the launch shaft. The location of the laser beam on the target is then transmitted to the operator, who controls the extension of the steering cylinders located in the articulated shield. The laser signal can be transmitted to the operator's console through electronic transmission and computer simulation or by video transmission to a screen located in the control console. Accuracies of ± 1 in. on line and grade on drives that are hundreds of feet in length are achievable with this method. However, mixed-face soils and unstable ground conditions can make achievement of such accuracies problematic.

During construction, specified tolerances may be difficult to maintain if relative pipe joint misalignments are excessive. Steering corrections should be gradual to prevent overcorrection. Problems resulting from overcorrection include eccentric loading at the pipe joints as well as "zig-zagging" of the alignment, as illustrated in Figure 4-3. The "zig-zagging" effect is caused when the operator applies too much steering to correct a deviation, causing the pipe to overcorrect and stray from the alignment in the opposite direction of the original deviation. Then, in reaction, the operator overcorrects in the other direction. To avoid these situations, corrections should be gradual, limited to approximately 1-in. correction over 25 ft of drive length.

4.4.2.6 Contamination

During the microtunneling process, the volume of excavated material is equal to the volume excavated for the shafts and the volume excavated for the pipe, increased by a bulking factor of 20 to 30 percent. This volume is far less than the volume of excavation required for open trenching and minimizes the amount of contaminated soil that must be treated or deposited at hazardous waste sites. At these locations, it is often advisable to minimize shaft sizes by specifying the installation of short lengths of pipe, e.g., 4 to 8 ft, to minimize the volume of excavated material at the shaft location. In addition, since dewatering is necessary only in the area of the shafts and only intermittently at these locations, the volume of contaminated water that must be treated or disposed of is much less with microtunneling than would be required with open-cut methods of construction. In areas of suspected contamination with suitable ground conditions, auger microtunneling may be especially effective because water is not needed for excavation and spoil transport, which greatly reduces the volume of potentially contaminated drilling fluids.

If onsite treatment of contaminated soil and groundwater is required, special provisions should be made to establish contaminated work zones where the contractor can perform this task. Depending on the types of contaminants, the contractor may be required to use special safety provisions, and all on-site personnel may be required to have hazardous-material training. Both of these provisions are costly and should be determined before bid to avoid delays and increased costs.

4.4.3 Shaft location and spacing

Locations and spacing should be carefully selected to minimize the number of shafts required. However, the spacing of shafts must not exceed the drive lengths achievable with the available equipment. Maximum shaft spacing varies according to the type of microtunneling equipment that is used, the laser/target system used, the diameter of the pipeline, whether intermediate jacking stations (IJSs) can be used, and the ground conditions. Diameter is important because it determines

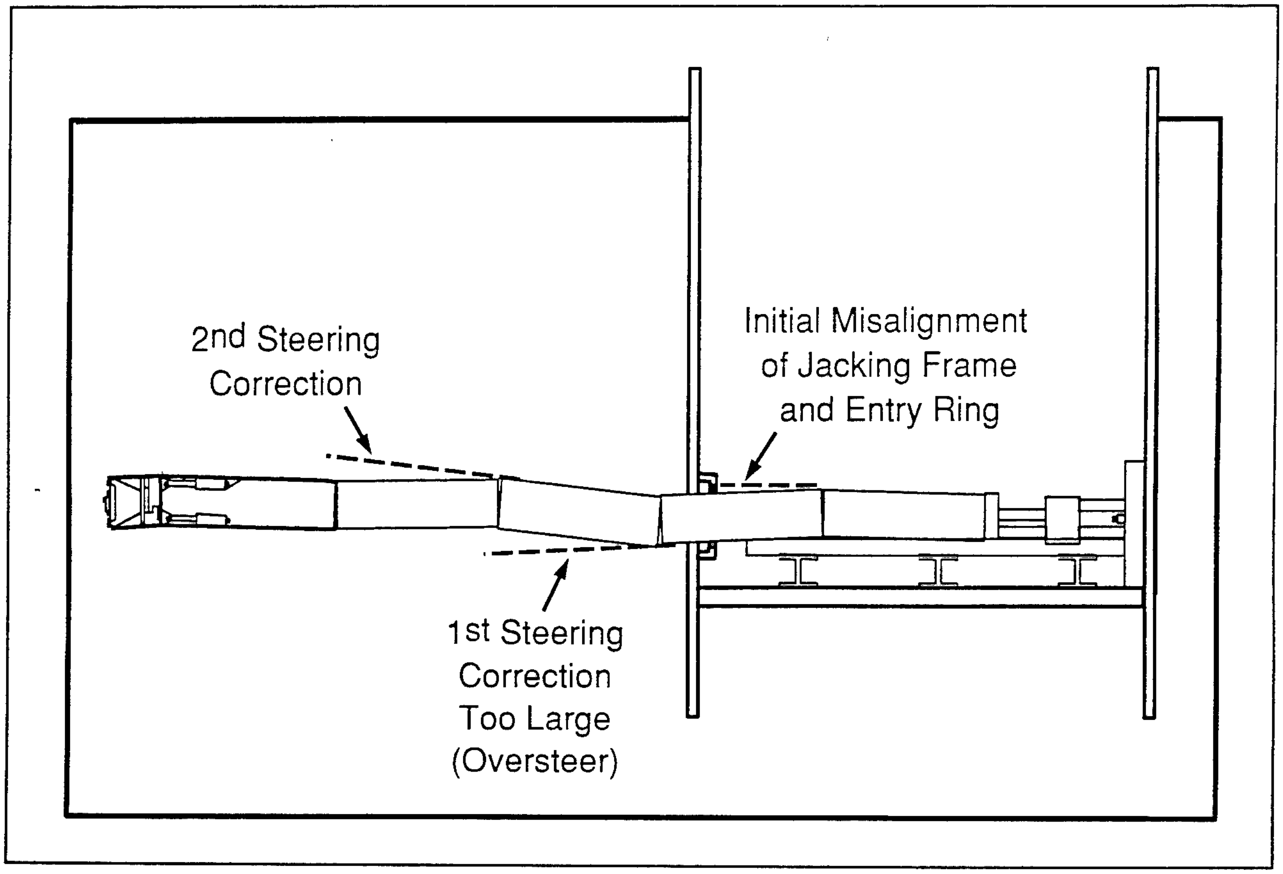


Figure 4-3. Importance of starting drive straight and effects of oversteering

the feasibility of using intermediate jacking stations. Currently, IJSs are not feasible on pipe with diameters smaller than 30 in. Shaft locations should be carefully chosen to minimize disruptions to traffic and businesses, to avoid overhead utilities and other interferences, and to allow safe work practices. Busy intersections should be avoided in favor of locations set back from the curb. Slight adjustments in shaft locations can sometimes avoid or minimize utility relocations. If limitations on allowable staging or lay-down areas at shaft sites exist, they should be clearly identified prior to bidding. In general, shafts are usually located where manholes are needed. The number of shafts can often be minimized by driving in two or more directions from one shaft.

In the case of slurry machines, the maximum drive length is also dependent on the pumping capabilities of the slurry system. When a slurry system is used, achievable drive lengths may be limited by the performance of the pumping system. The pumping system must be capable of transporting the material from the face of the machine to the surface at the launch shaft. In larger pipe installations, pumping capacity can be increased by installing booster pumps in the pipeline. However, in smaller diameter installations, e.g., less than 36 in., this may not be feasible as the booster pumps will not physically fit into the pipe or may block the transmission of the laser to the target in the heading.

Drive lengths can also be limited by laser performance. Laser beams will tend to spread as the length of the transmission increases, especially in the presence of humidity. In machines with computer guidance systems, the decrease in laser beam intensity as the drive length increases may result in loss of signal transmission to the control console. In the case of a video transmission, the size of the laser beam projected on the target may be too large to adequately determine position of the machine at lengths approaching 700 ft. However, this maximum length is dependent on the laser optics, brand, type, and strength of the laser.

In the case of auger machines, the length of the drive will be limited by available machine torque. Although motors can be installed in the cutterhead to provide torque to the cutting face, the length of the drive will be limited by torque required to rotate the auger string. In addition, placement of a motor in the heading can create additional problems due to the reaction of the laser beam to the excess heat created by the motor. The heat created by rotation of the auger flights in the casing can also affect the laser. However, air can be circulated through the pipe to lessen this adverse effect of heat on laser performance.

4.4.4 Pipe

When specifying the types of pipe to be allowed on a microtunneling project, all project requirements should be carefully evaluated to determine suitable products. Design criteria should include hydraulic characteristics, strength requirements, corrosion resistance of the pipe, ease of construction and repair, performance history, design life, and cost. In addition, dimensional tolerances must be established for trueness, straightness, squareness of ends, inner diameter, outer diameter, and thickness. Four pipe materials are commonly used in the United States: concrete, GFRP, vitrified clay, and steel. Some pipe manufacturers are currently developing alternate pipe materials that might be proposed for microtunneling applications in the near future. Figure 4-4 details relative pipe use by material in the United States.

It is unrealistic to assume that jacking loads are ever uniformly distributed around the pipe circumference and end-bearing area. Designers should assume eccentric loading, rather than uniform axial loading. All reasonable measures should be taken to keep maximum jacking loads within allowable levels and to minimize the eccentricity of the loads and resultant pipe stresses. These measures should include the following:

a. Pipes should be straight and uniformly dimensioned, have square ends, and have joints that are designed to allow efficient load transfer from pipe to pipe.

b. Pipe joints should be fitted with a spacer or compression ring that is highly compressible to aid in the distribution of uniform axial loads.

c. The jacking frame, jacks, and steering head should be properly aligned along the planned line and grade and should be square and true to the thrust wall to minimize eccentric loads.

d. Steering corrections should be made gradually (less than 1 in. in 25 ft) to minimize abrupt misalignment angles between two pipes, resulting in eccentric loads.

e. Adequate overcut (1/2 in. minimum on radius) should be provided around the pipe to allow steering corrections to be made and lubricant to more completely coat the pipe exterior.

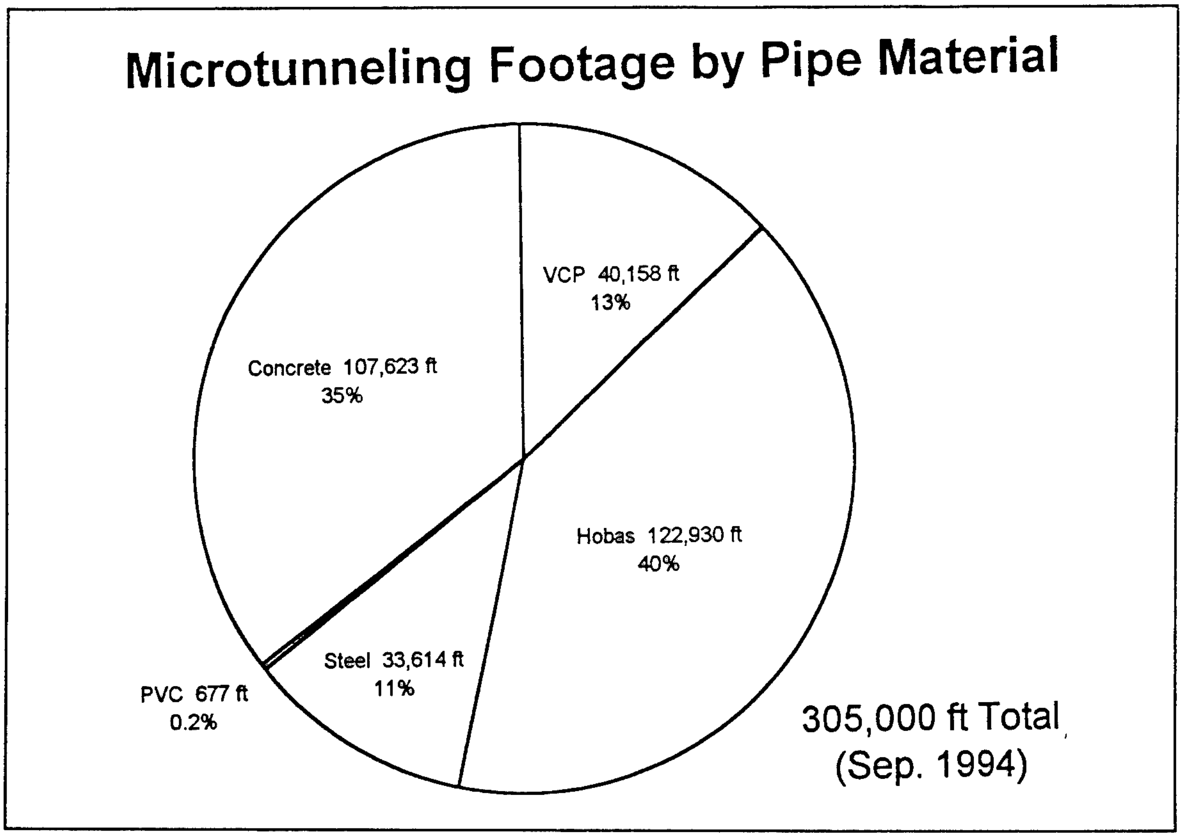


Figure 4-4. Relative pipe use by material as of September 1994 (Norris, Bennett, and Iseley 1995)

4.4.4.1 Pipe materials

Each of the four pipe materials listed has been successfully used in various applications.

Concrete pipe, sometimes fitted with a steel sleeve for axial strength and reinforcement (concrete cylinder pipe), has been successfully used in many microtunneling applications. It is often used in sewer projects and can easily be incorporated in existing sewer upgrade projects. Concrete jacking pipe is easily available and competitive in cost due to its widespread manufacture. Typical lengths include 8, 10, 16, and 20 ft. The strength of the concrete mix, as well as the wall thickness, can be adjusted to suit axial load requirements. In corrosive environments, designers may elect to have concrete pipe fitted with a PVC T-lock liner to help prevent hydrogen sulfide corrosion. In addition, lubrication ports can be installed during manufacturing or in the field by coring, if they are needed. Concrete pipe sections are typically relatively heavy, which can impact selection of the required crane for the microtunneling process. In addition, care is required to prevent spall at the joint section. Steering corrections should be gradual, and the axial jacking load should be applied uniformly by the jacking frame. Properly selected spacers or compression rings should be installed to help distribute loads evenly over the load bearing area of the pipe ends. Pipe joint considerations are discussed in more detail in subsequent sections of this report.

The use of vitrified clay pipe (VCP) for sewer applications is growing in the United States. Clay pipe has been a popular choice in Europe for years. Typically, strength requirements of clay pipe can be met with a smaller wall thickness than with concrete pipe. This makes the clay pipe lighter weight and easier to handle than concrete pipe of the same inner diameter. Unlike concrete pipe, there are only two main VCP manufacturers in the United States. VCP is typically manufactured in 4-, 6-, or 8-ft sections. Since vitrified clay has a relatively high axial strength, the strength of the pipe usually exceeds the jacking capacity of the standard jacking frames. Unfortunately, the vitrifying process does not allow for the installation of lubrication ports. The contractor must then rely on the lubrication port in the machine to provide adequate distribution of lubrication along the length of the pipeline. In addition, VCP tends to be brittle in nature, and extra care must be taken by the contractor when handling, storing, and installing the pipe to ensure that it does not break. As with concrete pipe, steering corrections should be gradual to minimize eccentric loadings that can lead to failure. Clay pipe distress may be manifested as cracks, usually starting at the joint, that may propagate along the length of the pipe section.

Centrifugally cast GFRP or Hobas is commonly used in highly corrosive environments. During manufacturing, GFRP is spun, or centrifugally cast. This manufacturing process makes it possible to vary the wall thickness and material properties according to the desired axial strength capacity. In addition, the pipe is very straight due to the spinning process that takes place during manufacturing, allowing very tight specification tolerances. The straightness of the pipe helps to eliminate eccentric loading that might occur if tolerances were relaxed. Unlike other types of pipe, the contractor or engineer can specify design load capacity and required factor of safety to the manufacturer according to the installation requirements. This determination, usually performed by the contractor, is based on predicted jacking forces, number and spacing of intermediate jacking stations, and a cost/savings ratio. Because of the inherent strength of the material, GFRP pipe has a much thinner wall than concrete or clay. The pipe sections are relatively lightweight and are much easier to handle than corresponding sizes of concrete, clay, or steel. In sizes up to 66 in. outside diameter (OD), a 10-ft section can be easily handled with a 10,000-lb boom-truck, eliminating the need for an onsite crane during installation operations. Hobas Pipe USA, Inc., is the only manufacturer of GFRP in the United States. Therefore, it is considered advantageous from an owner's perspective to allow use of Hobas along with other suitable pipe materials, rather than to specify Hobas, or any other pipe, as the only suitable pipe material. GFRP is manufactured in 20-ft lengths but can be cut to any reasonable length specified. A price premium usually applies to lengths shorter than 10 ft and lengths that are not evenly divisible into 20. Lubrication ports can be installed at the manufacturing plant or in the field. As with other pipe materials, joint failures can occur when abrupt steering corrections are made, especially those made near the jacking pit. In addition, sufficient overcut is critical to minimize the potential for damaging the bell sleeves at the joint. There are no known or documented cases of damage to sleeves when sufficient overcut has been used. Regardless, since the two documented cases of sleeve damage (that probably were caused by insufficient overcut), the bell sleeve design thickness has been increased 30 to 50 percent to add strength and minimize the potential for damage or problems.

Steel pipe is commonly used on water projects as a casing pipe, with a liner or secondary product pipe installed inside in a separate operation. Strength requirements are met by determining appropriate wall thickness. Typical installations have wall thickness varying from 0.5 to 1 in. There are numerous steel pipe manufacturers in the United States, making suppliers very cost competitive. Pipe can be manufactured to any desired length. Because of the inherent strength of steel, it is very difficult to cause failure of the pipe during installation. However, steering can be very difficult due

to the stiffness and rigidity of joints. Large steering jack pressures are required to correct or "bend" the line. In some situations, steering corrections can tremendously increase the jacking loads which may exceed the available jacking capacity of the jacking frame. In such cases, the jacking capacity may have to be increased or grade requirements sacrificed. Lubrication ports can be installed for injection of lubrication along the pipeline. Microtunneling projects using steel pipe typically have very slow daily production rates due to the amount of time required to field-weld the joint. Although steel is typically the least expensive of the four pipe options, need for a secondary carrier pipe and the time required to field-weld the steel pipe may override the cost savings. To offset high welding costs, a Permalok® joint can be used. This joint is described in detail in the pipe joint section.

4.4.4.2 Strength requirements

Required pipe strength should be based on the anticipated jacking loads for each drive. Appropriate safety factors for normal projects should range between 2 and 3. Each manufacturer has its own "typical" or recommended safety factor. Safety factors are very important as ultimate axial load capacity is often based on uniform compressive load tests of small coupon samples. However, due to initial misalignment, pipe tolerances, steering corrections, and geology, it is unreasonable to ever assume that the jacking loads will be uniformly distributed over the full end bearing area of the pipe. Therefore, the safety factor must be sufficient to account for the range of unknown or variable conditions and to ensure that the pipe will perform as intended after installation.

4.4.4.3 Pipe joints and couplings

Each manufacturer has recommended joint and coupling design details for its product. Typical joint and coupling details are shown in Figures 4-5 through 4-7, for concrete, GFRP, and VCP. Microtunneling pipe joints must be flush outside and inside with the pipe wall. If the joint/coupling protrudes outside the plane of the pipe wall, jacking load increases, and the soil surrounding the pipe will be disturbed, mixed with the lubricant, and dragged along with the pipe, which can lead to settlement on the surface. If the joint protrudes inside the pipe, flow characteristics will be impaired.

One common microtunneling joint is the flush wall bell and spigot. This joint is commonly used by the clay and GFRP pipe manufacturers. In this joint, the trailing end of the leading pipe is recessed and fitted with a sleeve or coupling, typically made of stainless steel for clay pipe, mild steel for concrete pipe, or fiberglass for GFRP pipe. The trailing pipe has a spigot that is grooved and fitted with gaskets. The spigot on the trailing pipe slides into the sleeve or coupling and creates a seal with the gaskets in the spigot section.

There are several types of joint configurations for concrete pipe. One joint type is very much like the bell and spigot joint found on the GFRP and clay pipe with a sleeve or coupling, fitted flush with the pipe barrel on the trailing end of the leading pipe. Another type of joint, the in-wall joint, does not have a sleeve but has a bell section created by increasing the inner diameter of the pipe, located on the trailing end of the leading pipe. The leading end of the trailing pipe has a recessed groove that mates to the bell end. This joint can be sealed with a rolling or confined elastomeric seal. There are problems associated with this joint as the bell end, on the leading pipe, tends to spall with eccentric loading. Another type of joint has trailing and leading ends that are mirror images of each other. In this joint, a sleeve, flush with the pipe barrel, slides over the recessed groove located on each pipe end. This sleeve is then sealed with two gaskets, one in each of the leading and trailing pipes.

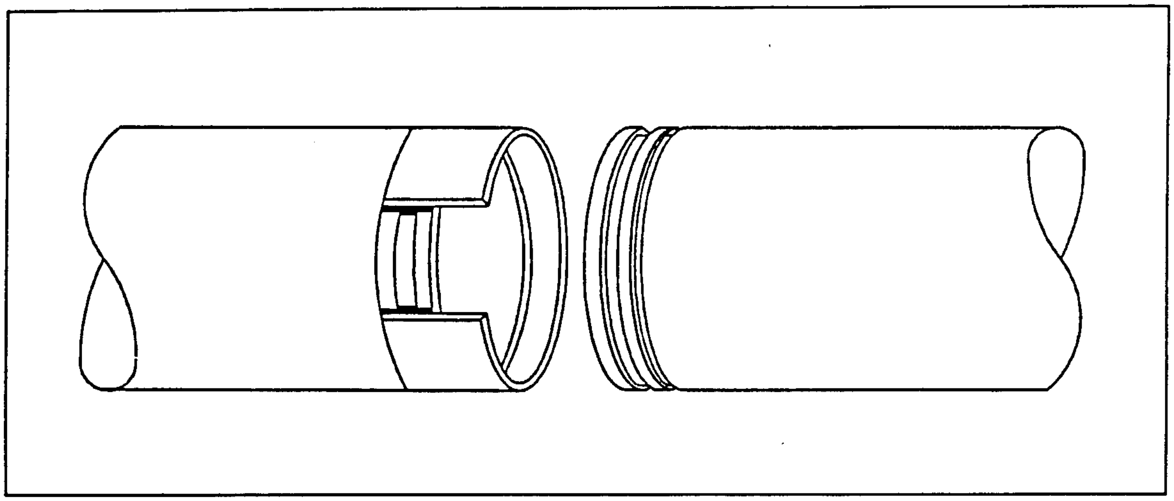


Figure 4-5. GFRP (Hobas) pipe joint

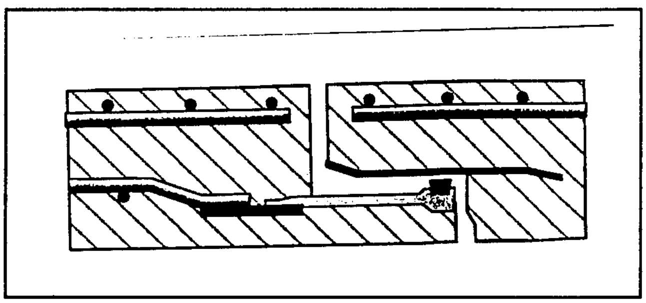


Figure 4-6. Concrete pipe joint

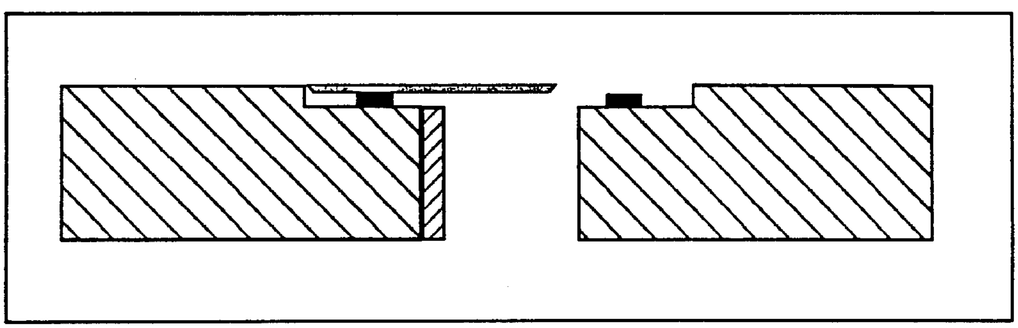


Figure 4-7. VCP pipe joint

There are two joint options with steel pipe: welded or Permalok®. One of the disadvantages of a welded joint is the lack of flexibility. Steering corrections can be excessively difficult and cause an increase in jacking forces. In some cases, jacking forces can increase dramatically and may exhaust the available jacking force from the jacking frame. In addition to increased jacking forces, there is a tremendous decrease in daily productivity when joints are welded as weld time can be a substantial part of the installation time. To increase productivity with steel pipe, Permalok® connections can be specified. The manufacturer, Permalok®, markets a "weld-less" barbed joint that is closed, using the force from the jacking frame. Connection times with the Permalok® joint are comparable to connection times with clay, concrete, and GFRP. Where time is of the essence, these connections can serve to accelerate a project where steel pipe is used. However, the joint is relatively expensive because of the high machining costs. Since the joint is available from only one manufacturer, it may be considered advantageous to the owner to allow its use, but not to specify its use in lieu of welded joints for steel pipe. In addition, Permalok® is a stiff joint resulting in steering problems similar to those with welded steel.

4.4.4.4 Pipe joint misalignment

Pipe joint misalignment can pose problems that lead to joint failure, leakage of the pipeline, or even inability to complete the drive. These misalignments can be caused by abrupt steering corrections, improper alignment of the jacking frame and jacks, improper pit installation procedures, pipe dimensions outside required tolerances, or inadequate spacers or compression rings. Figure 4-8 illustrates stress distributions associated with eccentric loading. Pipe failure, caused by angular deflections at the joint, will increase as the load and deflection angle increases. Failure usually comes in the form of a micro-crack that can then propagate and become a visible crack. If the load is increased, the crack may progress to catastrophic failure, which will typically not allow microtunneling to progress without extensive pipe repair. In addition, cyclic loading, inherent in the microtunneling process, increases the probability of joint failure at misaligned joint locations.

At locations where pipe joints are misaligned, loads will be increased due to the interaction between the pipe and the soil. This will, in turn, increase the jacking force necessary to propel the machine and pipeline. The problem associated with misalignments is then dramatically increased as the joint will have a higher probability of failure with the higher jacking loads. Therefore, the excavated hole, into which the pipes follow, should be as straight as possible.

4.4.4.5 Spacers or compression rings

Within the jacking pipe joint, a compression ring, also commonly called a spacer, is fitted between the end bearing area of the bell and spigot to help distribute applied loads more uniformly. The rings, typically made of 1/4-in. to 1/2-in. plywood, are attached to the trailing ends of each pipe and are compressed between the pipe sections during jacking. The spacers compensate for slight misalignment, pipe ends that are not perfectly square, gradual steering corrections, and other irregularities. Compression rings are critical to the jacking operation, especially in the event of high jacking loads, and should be included.

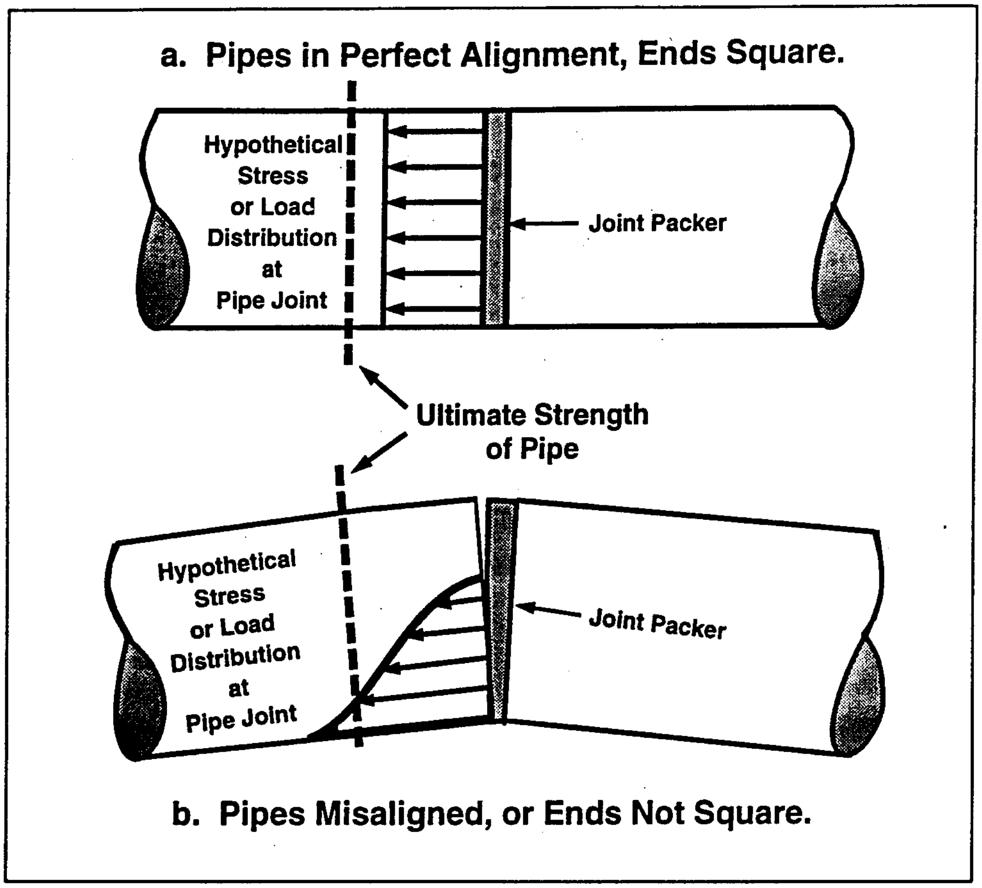


Figure 4-8. Effects of pipe misalignment on pipe stress

Clay pipe manufacturers supply compression rings with the pipe that are made of particle board or chip board and glued in place. With most other pipes, the compression rings are supplied by the contractor. The compression rings are usually made from plywood and installed in the field. Substantial research has been conducted at the University of Oxford to identify desirable characteristics of pipe spacers or packers (Milligan and Ripley 1989; Norris 1992). This research showed that the packer material should have uniform dimensions and should have a low Poisson ratio to minimize the development of tensile radial stresses at the joints. Although plywood has a higher Poisson's ratio than particle or chip board, in practical uses, it is sufficient for compression ring material. The research was performed with concrete jacking pipe, but many of the conclusions and recommendations are considered appropriate for GFRP and VCP.

4.4.4.6 Steering abilities

The steerability of the pipe is dependent, among other factors, on the allowable deflection of the joint. Concrete, GFRP, and clay pipe all have relatively flexible joint and coupling designs. Maximum allowable deflections are approximately equal in clay, GFRP, and concrete; therefore, steerability is approximately equal. However, steel pipe is much more difficult to steer due to the rigid welded joint which requires excess jacking forces to achieve steering corrections. In some

cases, it may not be possible to bring the pipe back on line and grade because insufficient jacking force is available to make the corrections.

4.4.5 Pipe annulus grouting

It is sometimes specified that the contractor will grout the annular space around the pipeline upon completion of the microtunneling operations. This grouting is intended primarily to minimize settlement. However, postinstallation grouting has proven to be ineffective in most cases. If the contractor continuously injects lubrication during the tunneling operations, the annular space will be filled by the lubrication. Typically, grout take (volume) will be very low when injected along the pipeline at appropriate pressures. If the contractor has not continuously pumped lubrication, the soil will usually move in around the pipe prior to the completion of the tunnel drive. Again, the grout take will be very low along the pipeline as there is little or no annular space to be filled. Typically, significant grout takes will be recorded only where voids exist around the pipe, either as a result of improper setup and operation of the machine, or as a preexisting condition. Significant grout takes may also be recorded if excessive grouting pressures are used. In such cases, grout may end up in manholes, basements, adjacent pipes, or parking lots.

4.5 Construction Considerations

4.5.1 Method/machine selection

Microtunneling methods can be separated into two categories: slurry and auger. Selection of machine type should be based on economic and technical feasibility. The primary factors in this determination are groundwater levels and soil conditions. Within the microtunneling methods, there are two types of cutterheads: soft-ground and rock. Ground conditions determine which cutterheads will be used. In addition to the categories and types of machines, the various manufacturers of microtunneling machines use somewhat different approaches in design that can affect the overall progress and success in different ground conditions. The selection of specific machines that meet performance criteria should be left to the contractor.

Slurry machines should be used in the presence of high groundwater pressures or where soil conditions are unstable. The pressure balance system inherent in these machines allows pipe installation in non-dewatered conditions while minimizing the potential for settlement or heave. The use of slurry machines is much more prevalent in the United States, probably due to their versatility. However, the use of auger machines can be advantageous in some cases. Slurry muck transport and muck separation are not as efficient as auger transport in relatively dry materials. Jacking loads will usually be higher for slurry machines used in dry sands. Stiff, over-consolidated clays present difficulties in excavation as the resulting wet, sticky muck is difficult to get into the slurry machine head and spoil transportation system. Advance rates usually suffer when slurry machines are used in these conditions. In addition, stiff, over-consolidated clays may swell when given access to water, resulting in high jacking loads. Methods for determining the potential for swelling of clays was discussed under the site investigation section.

As mentioned in the previous section, auger microtunneling might be favored in potentially contaminated ground. Auger machines may be used where groundwater heads are absent or less than

5 ft above the pipe invert and where soil types lend themselves to auger removal. These cases would include projects in dry sands and clays.

Jacking loads measured with slurry machines will be higher in clay soils than those with auger machines. This is due to the difference in operating principles of the two machines. In slurry machines, clay must be mixed with slurry and squeezed through the cutterhead openings.

4.5.2 Jacking loads

Estimated jacking loads should be determined for each microtunnel drive on a project. Accurate jacking load estimations are important to determine appropriate pipe wall thickness, the need for and placement of intermediate jacking stations, selection of jacking frame and jacking cylinders, machine overcut, thrust block design, and lubrication requirements. These estimations should be based on soil mechanics theory, combined with practical experience under similar microtunneling applications. The engineer should review and approve these calculations prior to construction. (Jacking records should be submitted to the engineer by the contractor during the drive, as recommended in the section on submittal requirements.)

The methodology established for the prediction of jacking forces is based upon the concept of combining the jacking force due to face pressure with that due to friction and adhesion to determine the overall jacking force. The components of jacking force are illustrated in Figure 4-9. The component of jacking force due to face pressure acts on the cutting mechanism of the machine and represents the penetration resistance of the boring and steering head into the ground. Actual face pressure must be maintained between the active and passive resistance of the soil. Therefore, the soil properties should be clearly established for the material through which the machine will travel. Proper calculation of face pressure requires accurate values of density, depth of cover, groundwater depth, cohesion, and internal angle of friction of the soil. The pressure is then converted to a force component, using the area of the face over which this pressure acts.

The component of jacking force due to friction and adhesion between the soil and pipe is controlled by the normal stresses and the effective coefficient of friction acting on the pipe. Both of these parameters vary along the length of the drive, depending on the depth of cover, soil properties, overcut, lubrication, misalignment, and steering corrections. The friction force is calculated by multiplying an effective friction coefficient by the normal force acting on the pipeline. The effective coefficient of friction will vary for different soils and to a lesser extent, for different pipe materials; its value usually lies within a range of 0.10 to 0.40. The values of normal force can cover a much broader range and can be more difficult to accurately estimate due to uncertainties about effective vertical and horizontal stresses and pipe areas over which these stresses act. However, accurate information about the soil properties and site conditions are vital to determine reasonable values for both the normal force and frictional coefficients.

The normal force is established by determining the vertical and horizontal soil stresses combined with the dead weight of the pipe and internal equipment. Depth of cover and soil cohesion are the most critical factors when determining vertical soil stresses because most microtunneling applications occur in relatively shallow depths where small changes in depth have dramatic effects on the overall vertical soil pressures. In the determination of normal soil stresses, recommendations have been

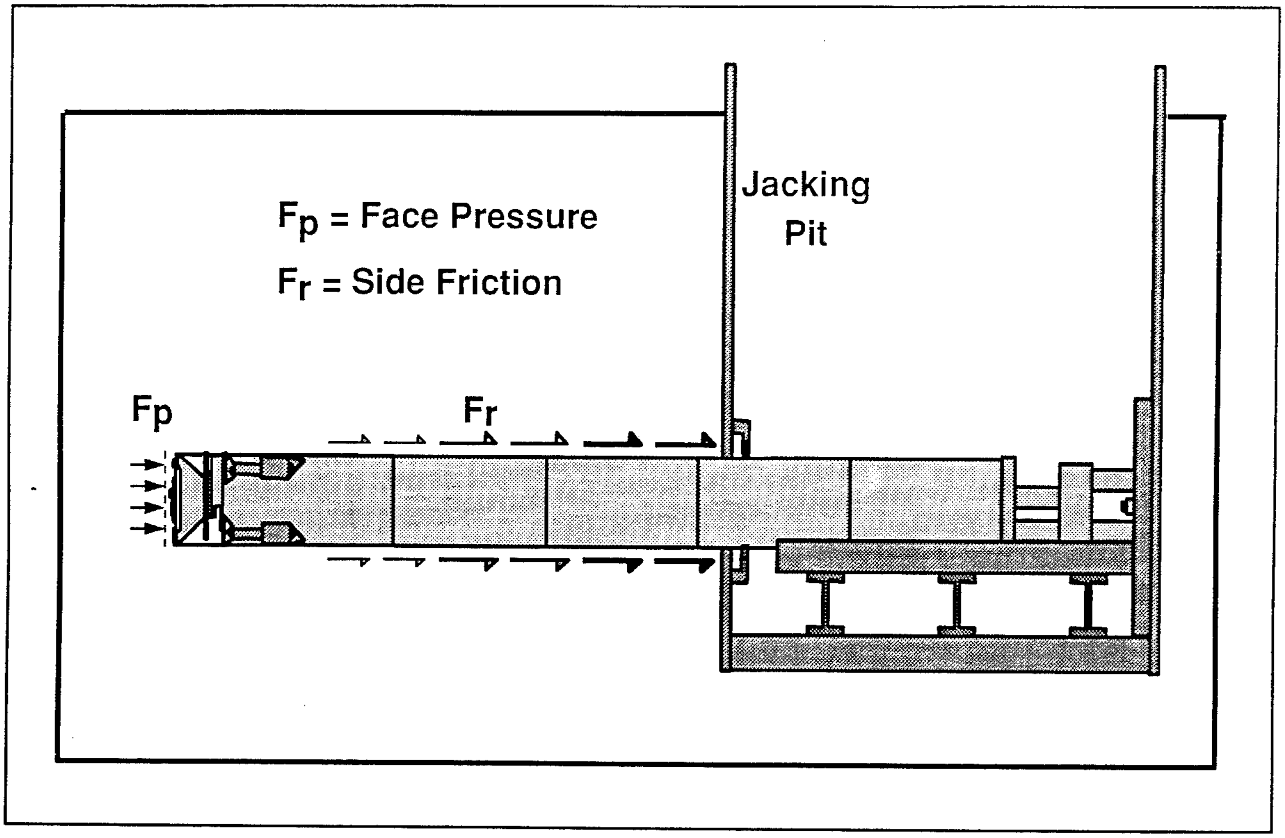


Figure 4-9. Jacking force distribution

developed by a number of individuals and regulatory agencies to be used in differing ground conditions (Stein, Möllers, and Bielecki 1989). Of these, the guidance provided by Terzaghi (1950) gives very good results in sand. When using Terzaghi's method in clays, the uncertainties involved in estimating vertical stresses and pipe contact area greatly complicate predictions and can lead to extremely conservative estimates. Possible explanations for the overestimation of jacking forces in clays are discussed by Milligan and Norris (1994).

Friction coefficients are a function of soil type, pipe material, overcut, and lubrication. Accurate determination of the friction coefficient can be difficult as it varies with soil type and overcut and is dependent upon even distribution of lubrication materials around the outside of the pipe. In a soil exhibiting cohesive properties, the overcut will stand open long enough for lubrication to be injected into the annular space. In these cases, the friction coefficient is based upon an interaction between the soil, lubricating fluid, and the pipe wall. However, if the soil is granular, the overcut will not remain open, and lubrication will be markedly less effective as the lubrication will mix with soil in the annular space, significantly increasing the friction between the pipe wall and the soil. Since the total friction force is proportional to friction coefficient, inaccurate selection of this coefficient can substantially change the estimated loads. Therefore, it is essential to determine an acceptable value for the friction coefficient. One of the best sources for this value is from the friction coefficient data

calculated for previous microtunnels that were constructed in similar soil conditions at similar depths and with similar pipe. This information is, by far, the most reliable source when determining appropriate friction coefficients. In the event that this information is not available, one may use his/her own judgment to make assumptions as to probable soil behavior and lubrication distributions and use tabulated values (Stein, Möllers, and Bielecki 1989) for the reaction between lubrication materials against soils and pipe. Alternatively, direct shear tests may be performed to determine pipe-to-soil friction. However, small-scale direct shear tests generally cannot provide a reliable assessment of the effects of lubrication between pipe and soil.

Using rule-of-thumb calculations for predicting jacking forces is not recommended. Since jacking forces are dependent on several factors that may vary over the length of the drive, use of a given normalized jacking force per unit area multiplied by the pipe surface area can produce erroneous and sometimes disastrous results. This method does not account for any soil properties, depth of cover, or overcut and would yield the same jacking force prediction whether tunneling through wet sands, sticky clays, swelling clays, or rock. Therefore, since more reliable methods are available, its use is strongly discouraged.

Some pipe manufacturers claim that jacking forces will decrease with the use of their product due to surface characteristics or the "smoothness" of their pipe. Their claim is that friction coefficients are markedly lower with smooth pipe materials. However, because lubricant is usually injected into the annular space, the change in friction coefficient, based on pipe material, is relatively small. Although laboratory tests may substantiate their claims, the analysis is based on a micro-property and its application is in a macro-environment. Documented decreases in jacking force are much more likely attributed to decreased surface area of the pipe, due to smaller outside diameter. The weight of the pipe and dimensional tolerances have a smaller effect.

4.5.3 Intermediate jacking stations

The use of IJSs can greatly extend the maximum length of a bore by uniformly distributing the large required jacking forces that are concentrated in the pipe near the jacking shaft over the full length of the bore. IJSs are composed of a traveling set of hydraulic cylinders contained within an expendable sleeve, typically made of steel. The jacks are placed between two pipe sections and are activated in sequence beginning with the section nearest the machine head and continuing to the jacking pit. When IJSs are used, the head is propelled by the first IJS, and the trailing jacking stations and main jacks advance the pipe string. While a preceding IJS is activated, the hydraulic valves of the trailing stations are kept closed to transmit the load back to the jacking frame and thrust wall. Upon completion of the drive, the jacks contained within the intermediate stations are removed. The joints are then closed underneath the sealing of the expended jacking station shell.

Currently, IJSs can be used only in pipe sizes of 36-in. diameter or greater because removal of the IJS requires a person to enter the pipeline. In addition, the cylinders and hydraulic hoses contained within the pipeline reduce the working area in the pipeline. A typical IJS for concrete pipe is detailed in Figure 4-10.

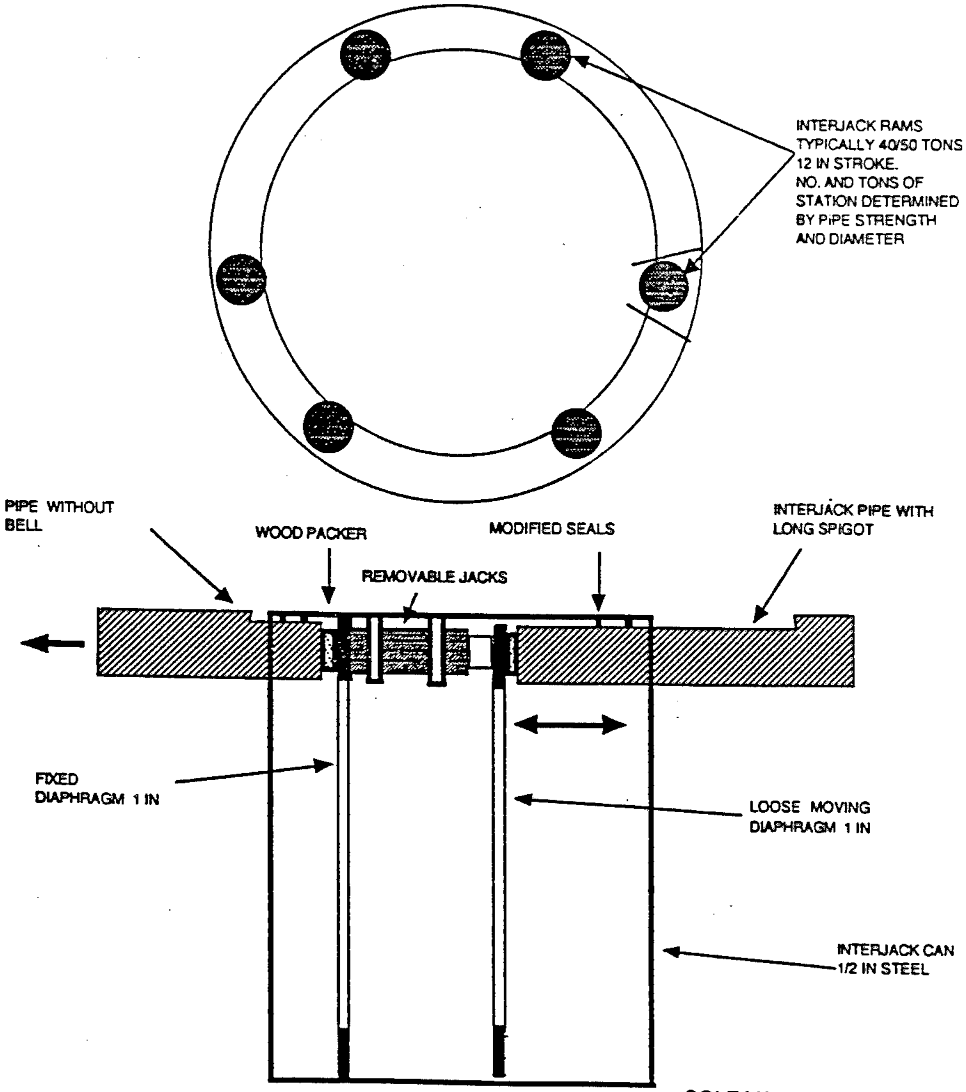


Figure 4-10. Intermediate jacking station

The placement of the IJS should be determined by comparing the axial design capacity of the pipe to the jacking force. Planned IJS should be placed in the line where predicted jacking forces reach 80 percent of the axial design capacity of the pipe. However, actual placement and use of IJSs in the pipe string may be adjusted based on the jacking loads experienced during construction. The contractor should have the authority and responsibility to place the IJS in the pipe string when the actual load reaches 80 percent of the axial design capacity, to minimize the potential for exceeding jacking pipe capacity.

4.5.4 Shafts

4.5.4.1 General

Jacking and reception shafts represent significant portions of the overall project costs and deserve corresponding care and attention. Proper shaft design and construction are essential for successful microtunneling operations. If the shaft design is inadequate, several problems can result that can affect the quality of the product pipeline, compromise site safety, or adversely impact existing facilities. These problems include insufficient thrust block capacity, deviation from line and grade, settlement in the area of the shaft, bearing failure and heave in the shaft bottom, bulging of sidewalls, and flooding of the equipment. The consequences can include delays, cost increase, accidents, and inability to complete the drive. Important shaft design issues are discussed in the following section.

4.5.4.2 Thrust blocks

The thrust block is placed in the shaft behind the jacking frame to distribute the thrust load to the soil behind the pit wall. If the thrust wall has insufficient capacity, it will move and can cause deviations in line and grade or may prevent development of sufficient thrust capacity to complete the drive. In worst cases, failure of the thrust block could lead to shaft failure.

Thrust blocks should be designed to take advantage of the passive resistance of the soil behind the wall and withstand the highest probable jacking load as determined by either the design axial thrust capacity of the pipe or the maximum jacking thrust capacity of the jacking frame. Because of the relatively large deformations required to develop full passive resistance in the soil behind the wall, an appropriate factor of safety for design is 2.0 or greater. Excessive deformations of the wall may occur if a lower factor of safety is used.

When the thrust block is built, special care should be taken to construct the wall square and true to the alignment. If the thrust block is not square to the pipeline, the jacking frame will tend to shift when the force is applied. This can cause the machine to deviate from the planned line or grade as the force from the jacking frame is not evenly applied to the pipeline. In addition, uneven distribution of force to the pipeline can cause pipe failure, resulting in leaks or expensive replacement or repair. In severe cases, the shifting of the jacking frame can cause the thrust wall to fail, which can lead to failure of the shaft.

It is also important to limit vibrations transmitted to the soil located directly behind the thrust wall. Repeated vibrations, such as those caused by slurry separation plants, can cause loss of strength of sensitive clays and can even lead to liquefaction of certain soils behind the thrust block, which can in turn cause loss of capacity and large deflections of the thrust block.

4.5.4.3 Floor slabs

A floor slab is typically placed in the floor of the shaft to provide a base for the jacking frame. The floor slab should be finished to the proper elevation so that minimal effort has to be expended to level the jacking frame. Improper placement of the floor slab can require extensive chipping efforts to level the frame. If the floor is not corrected and the jacking frame is not set at the proper angle for the slope of the pipe, the operator may have to oversteer the machine to correct for the launch angle. This can result in excessive and eccentric jacking loads, creating a range of problems.

In general, the floor slab should not be structurally tied to the thrust wall. Since thrust walls should be designed to take advantage of the passive resistance of the soil in developing the required load capacity, some deflection should be expected. If the floor is tied into the thrust wall, the floor will also shift at high jacking loads, which will change the alignment of the jacking frame and the laser if it is bolted to the floor. This can lead to deviations in required line and grade during the installation. To resist hydrostatic uplift, drainage should be provided below the slab, or the floor should be designed with enough dead weight to overcome uplift forces.

4.5.4.4 Laser mounting

The laser should be mounted independently of the thrust block. If the laser is mounted in/on the thrust block, even minor deflections of the thrust block will cause the laser beam projection to shift and result in inaccurate laser readings. If the thrust block deflection is large, the laser may not project onto the target system when load is applied to the jacking frame. Most contractors elect to mount the laser to the floor slab. An alternative is to mount the laser on a beam driven into the soil through a hole in the floor slab, although in the presence of high water pressure, this method may require additional measures to limit groundwater inflows through the shaft floor.

4.5.4.5 Groundwater/soil inflows

Whenever possible, shafts should be watertight. Groundwater and soil inflows into the shafts should be kept to a minimum. When soil is allowed to enter the excavation, voids and sinkholes often occur. These can create significant settlement on the surface, as well as hinder the tunneling process. If the tunnel machine enters a void, steering becomes impossible, and the machine will follow the path of least resistance, straying from the planned line and grade. In addition, slurry circulation losses will occur into these voids and can make it impossible to maintain stability of the heading. As a result, large settlements can occur due to overexcavation by the tunneling machine.

Localized settlement at the shaft can also be hazardous due to the concentration of heavy equipment around the perimeter of the shaft. Voids and settlement can cause serious injury if the soil collapses during the operation of the equipment. If soil inflows are noticed in the shaft, immediate measures should be implemented to stop the inflow and evaluate the locations and sizes of potential voids. This problem must be corrected immediately by grouting or other appropriate means.

4.5.4.6 Exit and entry of shafts

One of the most critical times in the microtunneling operation is during the launch and retrieval of the machine. Often this process takes place well below the water table. In those cases, it is critical that the contractor take precautions to prevent soil and water inflows into the shaft.

It is common practice to mount a seal to the wall of the shaft prior to the launch of the machine. These seals are typically bolted or welded to the shaft wall and are fitted with a neoprene or rubber gasket. As the machine launches, the gasket is distended and forms a seal around the outer diameter of the machine and eventually around the pipe. If groundwater pressures are known to be high, seals can be fitted with a double gasket configuration for increased protection against groundwater inflows. In addition to preventing soil inflows, seals are critical to the success of a microtunneling operation as they also prevent lubricant that has been pumped into the annular space from escaping into the

shaft. If an effective seal is not obtained at the shaft wall, the lubricant will not properly distribute around the pipeline, and jacking loads will increase.

In addition to a wall seal being mounted, the soil behind the launch seal must be stabilized to allow the launch of the machine. During launch, a hole must be cut in the shaft to allow entrance of the machine. Therefore, the soil behind the seal must stand for a limited period of time (typically from 20 min to 2 hr). There are a variety of methods currently used for localized soil stabilization. The most common methods are localized dewatering, on the outside of the shaft at the entrance and exit locations, or installation of grout plugs, typically a weak cement or chemical grout mixture, at the elevation of the bore. Weak bentonite-cement-grout mixtures can be very effective in preventing inflows and in stabilizing the ground. In addition, the low strengths of these grout mixtures allow the machine to easily excavate the grout plug during launch. In shafts constructed with sheet piles, another method is to drive two parallel sets of sheets along the launch face and stabilize the soil between the two walls with dewatering or grouting operations. Upon launch, the machine is driven through the first set of sheets and establishes a seal with the rubber gaskets mounted on the first sheet-pile wall. Once this seal is established, the second sheet-pile wall is pulled, and the machine progresses through the soil.

The selection of an appropriate launch method depends on groundwater condition, method of installation, and soil type. For pipeline projects below the water table, a microtunneling machine should never be launched without first implementing effective measures for soil stabilization around the shafts.

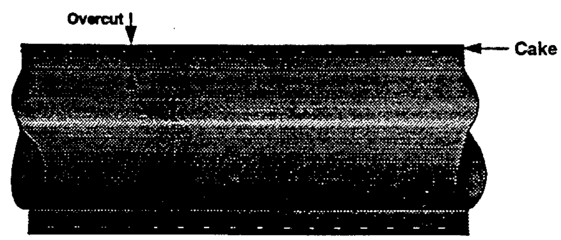
Some exit shafts may also require specialized procedures to prevent soil inflows. It is much more common to use dewatering methods, rather than grouting procedures, in these situations. If ground conditions permit and the area can be fully dewatered, a wall seal may not be necessary at the exit shaft. However, if dewatering is not possible, the installation of a can-type seal, which limits the amount of groundwater and soil inflow, may be advisable.

4.5.5 Overcut

Overcut may be defined as the difference in the excavated diameter and pipe diameter. Overcut may also be given as a radial annular dimension, so it is important to specify whether the overcut is measured on the diameter or radius. Determination of an appropriate machine overcut is often critical to the success of the job. Overcuts typically range between 0.5 and 3 in. on the diameter, depending on the outer diameter of the pipe. Ground conditions should be the predominant determining factor when deciding on the proper overcut.

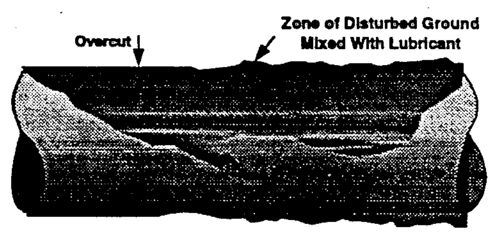
The amount of overcut can have an enormous influence on jacking loads, especially in relatively stable soils such as stiff clays. Significant effects are also seen in dense sands. In these soils, given enough overcut space, the dense sand will dilate as the shield passes through the soil, reducing normal stresses and shear resistance along the trailing pipe string. If there is no annular space for this dilation to occur, normal loads increase, increasing the overall jacking loads. In addition, the beneficial effects of lubricants are enhanced with the use of a larger overcut in stable soils because the lubricant more completely surrounds the pipe and promotes a stable opening, reducing the jacking load required to propel the pipeline forward.

A common tendency is to specify a small overcut with the thought that this will eliminate settlement potential. The concern usually expressed with using a large overcut has been that surface settlements may be unacceptably large. However, unacceptably large settlements are almost always due to the loss of stability at the face. Large settlements due to displacement of the ground into the annular space created by reasonable overcuts should not be of concern as long as ground conditions are well defined, sound operating principles are followed, and the machine is set up properly. Overcuts that are too small can be very problematic as the annular space, created by the machine, may be too small to allow for proper lubricant injection. In these situations, jacking loads due to friction can become very high and may limit the length of the run or even stop the forward progress of the machine. The effects of overcut and proper lubrication are illustrated in Figure 4-11. Steering can also be problematic if the overcut is too small.



a. Adequate Overcut, Generous Lubrication.

- **Lubricant More Uniformly Coats Pipe Exterior and Supports Soil**
- **Jacking Loads Reduced**



b. Inadequate Overcut, Inadequate Lubrication.

- **Lubricant Cannot Adequately Coat Pipe Exterior**
- **Lubricant Mixes With Soil, Rather Than Supports Soil**
- **Jacking Loads Increased**
- **Ground Disturbance May Be Higher**

Figure 4-11. Overcut and lubrication

Conversely, abnormally large overcuts can cause a range of problems, which include steering difficulties, loss of slurry, and settlement. If the overcut is large enough to allow "float" of the machine, the steering cylinders will prove ineffective as the machine cannot obtain sufficient thrust reaction from the surrounding soil needed for steering. This is particularly true in a mixed-face condition or where large rocks are encountered. In such cases, if the machine deviates from the planned line and grade, the operator may not be able to steer the machine back to the proper location. Settlement and loss of slurry can be important concerns when large overcuts are used in conjunction with shallow cover ($h/d < 3$).

Another common problem that can affect overcut is the variation between manufacturers' outside dimensions for the pipe and machines. It is a natural tendency for a contractor, with or without support from the pipe and machine manufacturers, to use available equipment on a new project. In some cases, the shield OD may be several inches larger than the pipe OD, which would result in an overcut larger than desirable. Conversely, the shield OD may be approximately the same as the pipe OD, resulting in insufficient overcut. In this case, a hardened band can be installed on the shield to increase the effective overcut. In general, machine overcuts should not be less than a half inch on the diameter. Larger overcuts may be appropriate for pipe sizes greater than 36-in. OD, and in stiff to hard clays, dense sand, and rock.

4.5.6 Lubrication

Both auger and slurry microtunneling machines are equipped with lubrication systems intended to inject lubricants in the annular space created by the machine overcut. Use of lubricants can be very effective in reducing jacking loads. The reduction of achieved jacking loads depends on a number of factors including overcut, spacing of injection ports, and soil conditions. When proper lubrication materials and methods are used, reductions in jacking loads by as much as 50 percent have been claimed. However, recent documented tests conducted on the CPAR project at WES, indicate that a more reasonable jacking force reduction is 20 to 30 percent. Caution should be used when estimating expected benefits of lubrication because, in some soils, eliminating lubrication could result in extremely high jacking loads, and even failure to complete a drive. The reader is further cautioned that the measured decreases of 20 to 30 percent in jacking loads were recorded over short distances where different types of lubricants were being evaluated. Some residual effects of a previously tested lubricant may have influenced the base jacking force measured prior to injection of the subsequent lubricant.

The most commonly used lubrication product is bentonite. Dry bentonite should be thoroughly mixed with water in a mixing plant on the surface and allowed to fully hydrate. It can then be pumped to the lubrication ports in the machine. Other lubricants include polymers or bentonite-polymer mixtures. In some situations, such as tunneling through highly plastic "fat" clays, polymers can be used to reduce the amount of the slurry water being absorbed by the clays which may reduce swelling pressures and jacking forces. In any application, bentonite or other lubricants are relatively inexpensive components of the pipe installation process and their use is generally recommended. Lubricants should be used continuously from the beginning of the drive. If their use is delayed until jacking forces reach critical levels, it may be too late to achieve much benefit.

In pipes with a 36-in. diameter or larger, lubrication ports may be installed in the pipeline and can be incorporated in the lubrication system as the pipeline progresses. This allows for continuous pumping of lubricant and helps to ensure more uniform distribution of lubricant around the pipeline.

Lubrication ports are not practical for pipe diameters less than 36 in. because personnel entry is required to remove the injection hoses and fittings and to plug the lubrication ports. In addition, lubrication ports are not practical for vitrified clay pipe due to the manufacturing constraints, but can be incorporated into other pipe materials.

4.6 Bid Documents

4.6.1 General

The bid documents, prepared by the owner/engineer, should provide the contractor with all vital information needed to prepare competitive bids for construction. Microtunneling bid documents should include all of the items required in typical pipeline or other construction projects such as Invitation for Bids, Scope of Work, Bill of Quantities, Specifications, Plans, Bonds, etc.. However, since microtunneling is a specialized installation technique, some of the bid documents will have unique requirements.

4.6.2 Minimum performance requirements and performance period

Minimum performance requirements are established in the contract documents to ensure that the pipeline, as installed, will perform as designed. The primary criteria typically established for gauging performance include line and grade, hydraulic characteristics, water infiltration, and protection of adjacent structures, other utilities, building foundations, streets, roadways, bridges, tunnels, rail-lines, etc. Secondary criteria are often established to guide the contractor and ensure that the primary criteria are satisfied. Secondary criteria may include shaft locations and sizes, manhole locations, and safety factors to be applied to jacking loads; minimum tolerances for pipe diameter; methods and material specifications; pipe joint requirements such as squareness, trueness, and roundness; allowable settlement and heave at specified distances from the installed pipeline or at specified locations; requirements for groundwater control; tolerances for line and grade and relative pipe deflections; requirements for control of traffic, noise, and dust; overcut, lubrication, and grouting of the annular space around the pipe; allowable work hours; and safety requirements.

4.6.3 List of applicable references and standards

A list of references and standards for equipment, materials, safety, etc., should be provided to the contractor for use in planning and bid presentation.

4.6.4 Geotechnical site-investigation report (including interpretations)

A complete site-investigation report, including interpretations, should be presented to the contractor prior to bid time. Details on site-investigation reports can be found in the Site-Investigation section of this report. As mentioned in this section, full details on expected or known contamination levels of soils and groundwater should be provided to potential bidders.

4.6.5 Minimum qualifications

To ensure a safe, efficient, high-quality project, the owner should present a list of minimum qualifications to the potential contractors. These minimum qualifications typically include a minimum number of microtunneling projects or footage successfully completed by the contractor. An emphasis should be placed on projects with conditions that closely match the project to be bid. The contractor should furnish a list of references where microtunneling techniques were used in similar ground conditions. Submittal of resumes of key staff and consultants may be appropriate, especially on large or difficult jobs. Financial data on the contractor and any subcontractors should also be furnished. The deadline for submittal of these qualifications should be clearly specified and should be prior to contract award. Owners may elect to call for qualifications prior to bid, in the form of a prequalification package. It should be noted that a prequalification process could raise the cost of the project by limiting the number of bidders. However, since microtunneling is a relatively new technology, prequalification can be used to reduce the risk to the owner and may be especially appropriate on large complex projects. The goal of the prequalification process should be to ensure that the work will be performed by a qualified contractor and that the public interests are served.

4.6.6 Minimum submittal requirements (from contractor to owner)

To ensure compliance with the requirements of the specifications, a number of submittals should be required from the contractor. The specifications should clearly state the minimum submittal requirements for the contractor. The timing of the various submittals should be in accordance with the submittal schedule as presented in the contract. Submittals detailing the construction process, pipe, jacking and receiving shafts, lubrication, and equipment should be approved by the engineer prior to construction. Other submittals, such as as-built construction records and complete jacking records, will be submitted throughout the construction process.

4.6.7 Requirements for protecting existing structures and site features

When necessary, the owner should specify the level of noise, lighting, traffic interruption, work hours, etc., which will be acceptable during construction. In addition, if the contractor disturbs the surrounding environment, existing utilities, or structures, the contractor should be required to restore them to their original condition.

It is important to note that microtunneling contractors sometimes elect to work 2 or 3 shifts per day when permitted to do so. On some projects, it is imperative that the forward progress of the microtunneling machine be continuous because jacking loads can build up dramatically if progress ceases for an extended length of time. The buildup of high jacking loads may prevent the machine from advancing or may lead to pipe failure. The specification should allow the contractor to establish and vary work schedules, including the option of working extended hours, unless unusual overriding project constraints exist.

4.6.8 Monitoring requirements

The owner should outline specific monitoring requirements for the pipeline. These should include spacing for surface monitoring points as well as a list of specific machine performance data that should be submitted to the owner. Items on this list might include the following: settlement data, location of settlement points, continuous line and grade information throughout the length of the

drive, machine thrust forces, slurry flowrates and pressures, machine torque values, advance rates, and laser positions on the target system of the machine. The interval between or frequency of data readings should be clearly stated as well as the timing on the submittal.

4.6.9 Remedial action requirements

Owners should attempt to formulate a course of action for the contractor to follow in the event that the job does not go as planned. Even the most comprehensive contract may not cover all of the problems that might arise during construction. These remedial action requirements should cover any foreseeable problems, and these problems should be identified in the contract.

Along with obstructions and changed conditions, other typical problems which may occur on a microtunneling project include the following: deviations from line and grade, slurry migration to the surface, thrust wall deflections resulting in steering problems, slurry disposal problems due to high levels of fine particles that stay in suspension, and settlement at the portal as the machine exits the pit.

The most common problem associated with microtunneling is encountering an obstruction or material that was not identified on the geotechnical site investigation report. These problems should be addressed on a case-by-case basis. However, a plan should be established by the owner that specifies procedures for addressing such situations so that valuable time is not lost when the event occurs. Since the predominant cost associated with microtunneling is the equipment, an established plan for handling problems that stop the project can reduce costly stand-by charges that will accrue while the contractor waits for direction by the owner. Regardless whether the delay is judged to be a changed condition for which the contractor is entitled to payment, the costs of delays are significant and will be borne by one or more of the parties to the contract. It is in the best interest of all, therefore, to minimize delays in the decision process to get the job back on track.

Along with obstructions and changed conditions, other typical problems which may occur on a microtunneling project include the following: deviations from line and grade, slurry migration to the surface, thrust wall deflections resulting in steering problems, slurry disposal problems due to high levels of fine particles that stay in suspension, and settlement at the portal as the machine exits the jacking shaft.

4.6.10 Measurements

Measurements for payments should be made from center to center of manholes or to the inside face of terminating structures. Procedures for measurement should be clearly stated in the contract to avoid misinterpretation. Microtunneling is typically bid on a cost per unit length installed or by reach/drive. Specifications should require remeasurement by both the owner and contractor when a discrepancy in measurement exceeds a specified level.

4.6.11 Payments

Payments for job activities should be based on the unit price bid for the particular activity. The breakdown of activities for bids and payments typically include but are not limited to mobilization, installation of shoring, excavation of jacking and receiving shafts, installation of pipeline (on a per-foot basis), and demobilization. Dewatering and stabilization are typically included in pit excavation, but may be considered separately, especially if the groundwater is contaminated.

4.6.12 Dispute resolution plan

Because of the variety of conditions that are typically encountered on a microtunneling project, many of the potential problems are not foreseeable and may not be covered in the contract. As a result, microtunneling jobs may be particularly vulnerable to disputes. To avoid lengthy and costly court battles, a good dispute resolution plan should be incorporated into the contract and presented to the contractor. The dispute resolution plan should attempt to resolve disputes in a fair and timely manner and avoid legal proceedings. Some plans require both parties to submit to arbitration by a third party when the parties cannot resolve the dispute on their own. Dispute Review Boards and mediation are alternative methods sometimes used in settling disputes. Maintenance of complete jacking records, settlement reports, and as-built line and grade documentation will also serve to reduce disputes.

4.7 Submittals from Contractor to Owner

4.7.1 General

Submittals requested by the owner from the contractor are critical to ensure compliance with the project specifications. In addition, they provide the basis for monitoring details of the project. These submittals, or portions of, can be provided at various points during the procurement and construction process, including the following: prior to tendering or bid opening, prequalification of the contractor and the pipe supplier to allow a thorough technical evaluation of the product and contractor without the influence of the contract amount or the bid price; with the bid submittal package; after contract award but prior to construction; during the construction process; and at completion, for use in as-built drawings, certifications, and contract close-out.

The submittals of interest include details on construction methods, project scheduling, qualifications, certifications, quality control, construction records, and safety.

4.7.2 Construction methods submittal

The construction methods submittals are a detailed explanation of the various steps involved in the construction process. They should include equipment, specific manufacturer's literature pertaining to the project; techniques, a methodology statement detailing the operation of the equipment to ensure product pipe accuracy; materials, including pipe material and lubrication; and other permanent and temporary features, including details on shafts, dewatering systems, manholes, thrust walls, etc. These submittals should detail all equipment used for the microtunneling operations including the following: intermediate jacking stations, slurry and feed pumps, control systems, slurry tanks complete with de-sanding methods, jacking frames, and slurry by-pass systems.

4.7.3 Sequence of operations and scheduling

The Contractor should provide a sequence of construction corresponding to the various items reported in the Construction Methods submittal. For projects with multiple tunnel drives, estimated drive and set-up times should be submitted to the Owner.

4.7.4 Layout of operations

Construction site layout information is important to the owner to verify that the operations do not infringe on personal property or unnecessarily interfere with any public or private operations. A sketch should be submitted (marked copies of the project construction plans may be satisfactory) indicating storage areas, pit locations, construction staging areas, and locations of major equipment (slurry tanks, control containers/cabins, crane/boom-truck, slurry hose rack, bentonite lubrication pumps, etc.).

4.7.5 Spoil management

This submittal should address the methods of removing spoils from slurry tanks, equipment to remove the spoils from the site, disposal methods, and locations where the material will be disposed. This submittal should also include tests for potential contamination of spoils as well as management and disposition of materials that are determined to be contaminated. When tunneling in soils with a high percentage of fine particles, it may also be necessary for the contractor to submit a method for removing the soil from the slurry so that the slurry water can be discharged to the sanitary sewer.

4.7.6 Contractor qualifications

The contractor must provide verification of qualifications to the owner. The number of references required by the owner should be furnished. References should have direct knowledge of the contractor's experience on projects, which include installation of pipeline with the microtunneling method. Complete names, affiliations, addresses, and telephone numbers should be furnished so the owner may contact the references to verify satisfactory performance. The contractor should furnish background information on key personnel to allow the owner to ensure the equipment operator and other key staff have adequate, relevant experience on similar projects and in similar ground conditions. The contractor should provide documentation of at least the minimum amount of project experience required by the owner for tunnel operators and superintendents. This should include a list of project experience for all key personnel. Supporting financial data on the company should also be submitted to ensure that the contractor and/or pipe supplier will be available in the long-term to support the product. Similar background information should also be supplied on all subcontractors.

4.7.7 Specialists/consultants qualifications

For large or complex projects, the qualifications and experience of any specialists or consultants that the contractor plans to use to satisfy owner prequalification requirements should be submitted. For small or less complex projects, use of consultants and specialists may be unnecessary, and this submittal requirement may be omitted.

4.7.8 Drilling fluids and lubricants

The contractor should submit information on all proposed drilling fluids, additives, lubricants, and other expendable materials planned for the project. Submittals should include material safety data sheets on each material along with a description of where the material will be used and its purpose in the construction process.

4.7.9 Quality assurance/control plan

The contractor's submittal should clearly address how he will satisfy all specification requirements on quality control items related to qualifying materials, construction procedures, and performance testing of the finished product. The submittal should detail procedures for ensuring that owners' specifications for line and grade tolerances, dimensional tolerances and load capacity of the product pipe, allowable settlement and heave, ground control, and infiltration testing will be met. All tests and monitoring procedures should be submitted to the owner prior to the construction process. Installation quality control is typically evaluated through field measurements of selected settlement points, sample measurements and tests of physical properties, and pipe dimension measurements and leakage tests. Pressure testing of pipe joints is often performed in the field upon completion of the installation. Quality control efforts should be outlined for equipment maintenance and repair in the event of an onsite breakdown.

4.7.10 Ground monitoring plan for settlement and heave

A detailed plan for monitoring settlement and heave should be established prior to construction. This plan should include surface monitoring points, in an array above the crown of the pipeline, as well as subsurface points on nearby utilities and foundations of existing structures. For sensitive nearby structures, preconstruction crack surveys as well as periodic crack surveys during installation may be desirable. Frequency of monitoring should be established in zones near the tunnel heading. Ground monitoring should begin well before the launch of the tunnel machine to establish an accurate baseline from which to measure settlement or heave.

The ground monitoring plan, as submitted by the contractor, should be comprehensive and based upon some basic principles as listed below. Project construction should begin in the least critical area so that the contractor will have the benefit of learning how the machine reacts in the soil conditions before entering critical areas. Ground monitoring should take place at the levels and locations of concern, not only on the surface. Increased monitoring should take place prior to reaching critical zones to ensure that the operation is proceeding as planned. Monitoring points should be concentrated near shafts as this zone can have the tendency to settle due to the shaft excavation.

4.7.11 Safety plan

The safety plan is critical to the construction operation to ensure that the public and workers are protected from construction hazards. This safety plan should include a submittal of the contractor's safety procedures for all workers. The safety plan should include a confined-space entry program for entry into construction pits and the pipeline, complete with a gas monitoring program to ensure all workers have access to breathable air. The plan should address traffic control and shaft maintenance to ensure public safety. All safety procedures should be in accordance with local, State, and Federal standards. It should be noted that some States have implemented safety requirements for microtunneling and pipe-jacking operations. In California, for example, safety requirements are defined by the Mining and Tunneling Divisions of OSHA, and safety personnel are required to carry a gas-testing license issued within that State. The contractor should present documentation of all licenses to the owner to ensure that the contractor complies with all appropriate safety requirements.

4.7.12 Construction records

Various submittals are required during the construction process to monitor the project. These include the following: preconstruction survey reports, documented as-built conditions, construction logs, materials installed, extent and causes of delays, locations of affected areas, and unusual problems or conditions encountered. Complete machine performance or jacking records should also be submitted by the contractor. These machine performance records should include, at a minimum, slurry flow rates, jacking/thrust loads, machine torque measurements, advance rates, laser locations, and machine locations throughout the length of the drive.

4.7.13 Estimated jacking loads

The contractor should submit the estimated jacking loads for each drive in the project. These predictions should be established using standard soil mechanics theory and supported by data collected on previous jobs in similar soil conditions. These predicted loads should be compared to the axial design capacity of the proposed pipe, including factor of safety, and the contractor should submit proposed intermediate jacking station locations based on these estimations.

5 Recommendations

5.1 General Recommendations

The research conducted under this project has focused on rehabilitation of existing pipelines using CIPP and FFP and installation of new pipelines using mini-HDD and microtunneling. Significant advances have been achieved in understanding these processes, applications, and current limitations. Recommendations, offered in the following subsections are keyed to needs in each of these areas. However, some general recommendations are appropriate for all of these trenchless methods and may be applicable for areas that could not be included in this effort, e.g., large-diameter HDD for pipeline river crossings, pipebursting, slip-lining, rehabilitation with localized repair methods, etc.

In all areas of trenchless technology, an urgent need exists to train operators and installation crews. The manufacturers and suppliers are doing a credible job in this regard, but as the trenchless market rapidly expands, it is unlikely that these efforts will be sufficient to meet growing needs. Formal training programs should be developed with input from all key parties (manufacturers, suppliers, contractors, and engineers) that can produce qualified installation crews and operators. One such program exists at Bridgewater College in England for microtunneling machine operators. The Charles Machine Works, Inc. has recently opened a facility for training operators to use their products. Efforts such as these should be encouraged and expanded to all areas of trenchless and underground construction. An appropriate venue might be community college curricula, developed and taught by experts in that field, using simulators, virtual reality, and other cutting-edge educational tools. The programs should produce qualified operators and technicians. Certification and licensing boards should be established, patterned after those for water treatment plant operators, engineers, and surveyors, medical and other professions, where licensing or certification and periodic recertification are based on successful completion of required training and examinations.

Training is also needed for owners' representatives and engineers. Over the last few years, seminars and conferences have been held to increase awareness and general knowledge of trenchless technology. These efforts have been quite successful and continue to provide benefits. However, urgent needs exist to take these efforts to the next level, that is to develop highly focused training venues that provide detailed guidance for planning, design, and construction using trenchless methods. Trade journal articles that, beneath the glamor and glowing success facades, hint at real problems encountered and cases of ill-conceived plans and specifications of a few recent projects bear testimony to the need for realistic, focused training. Engineers need guidance on the practical limitations and problems with each method to make informed choices and develop practical designs, plans, and specifications.

In this regard, it is recommended that model or guide specifications be developed for each of the major trenchless methods addressed in this study. These model specifications should be based on the guidelines provided in this report, supplemented by case histories and credible references. This need also exists for areas of trenchless technology not addressed in this project, especially for rapidly growing methods such as pipe bursting.

More open discussion is encouraged in the technical journals and trade magazines of case histories where problems were experienced. Far more can be learned from honest discussion of problems and solutions than from glowing success stories. Owners, engineers, and contractors need to be honestly informed of realistic expectations to allow rational growth and minimize costly failures.

5.2 Recommendations for Pipeline Rehabilitation

A study of the limit states of liners and a design approach that takes into account levels of confidence in various known and unknown influencing factors should be developed. Research into models other than the unrestrained ring buckling model that more accurately predict the behavior of constrained liners is also necessary. Such models could enable designers to explicitly include parameters in the design equations which are currently included in the factors of safety. The inclusion of these parameters would provide designers with greater confidence and potentially more efficient designs.

A standard test method for evaluating the long-term behavior of liner systems under hydrostatic test pressures is needed. The procedures developed under this CPAR R&D project should serve as the basis for the standard. Further experimental research is needed to verify the behavior of pipeline rehabilitation systems considering parameters not included in this study, such as the effect of gap size between host pipe and liner, ovality, and chemical effects on the long-term performance of these products. Further research is needed in the design of these systems which may consider the types of boundary conditions and behavioral characteristics that are more representative of actual field conditions. For example, tests of liner systems in pipes with bends, offset joints, or other defects are needed. In particular, more research should be conducted on different pipe diameters and dimension ratios to develop an improved empirical model for the determination of both the short- and the long-term behavior of liners. This research would assist in determining the technical envelope of applicability of liner systems.

While it is recognized that laboratory research can reduce the costs and risks associated with field trials, there is no effective substitute for the testing of products under actual field conditions. There are thousands of feet of liner systems which have been installed in the United States, and some have now been in place for several years. Records should be maintained on the performance of these liner systems, and those which perform exceptionally well or poorly should be documented as case studies. This could help engineers in designing and specifying liners, and it could help manufacturers in enhancing their products for better performance.

The ability to rehabilitate service laterals using liner systems is an emerging technology that holds much promise. Sealing lateral tie-ins and making localized repairs are also relatively new techniques which should grow in acceptance. These and other technological advancements should be studied by

the industry as a whole, and where appropriate, testing standards, construction procedures, and design specifications should be developed.

5.3 Recommendations for Mini-HDD

Improvements in practice for mini-HDD can be achieved through better documentation of as-built installations to include submittal of plan and profile views of as-built lines, including intermediate locator readings, and documentation of fluid usage in gallons/per foot of bore for both boring and reaming. (Typically, total fluid usage is recorded for the bore and divided by length to calculate fluid usage in gallons/per foot). More precise measurements of fluid usage rates could be obtained using flowmeters in the inlet line. Such measurements could provide valuable information to the operator and the owner, especially sudden increases or decreases in fluid usage. In addition, fluid injection pressures are currently monitored at the slurry tank. Measurements at the cutter bit would provide more useful information. Viscosity measurements should also be recorded at the beginning and end of a bore to allow better control of the drilling process and stability of the bore. Finally, any unusual observations or difficulties should always be recorded and submitted to the engineer. Continued developments to improve the accuracy and maximum depths of locator systems should be encouraged, as well as continued improvements in electrical strike warning systems.

Expansion of mini-HDD applications could be achieved through research and development that could help solve difficult challenges. Efforts are underway in some of these areas and should be encouraged and supported. For example, the challenges facing the United States and many countries in environmental remediation could greatly benefit from trenchless technology applications. Potential mini-HDD applications include installation of horizontal monitoring and treatment wells and underdrains at contaminated sites. Key issues requiring further development include screen/filter materials and methods for screened interval installation and well development, as well as drilling fluids that are biodegradable to minimize adverse impacts on well efficiency. Further development of air drilling systems would eliminate this problem, but borehole stability must be ensured. Use of sacrificial perforated casing installed during the pilot bore or reaming process may offer solutions in some cases. The incorporation of sensors into the drilling head that can detect contaminants, such as volatile organics, could lead to significant cost reductions in applications such as underground storage tank remediation projects.

The mini-HDD method has enormous potential for military applications, some of which could then be adapted to civilian use. For example, research conducted by WES recently demonstrated that mini-HDD has high potential and could be very effective in rapid creation of tank "hull down" protective positions and rapid creation of obstacles to approaching enemy troops, allowing safe withdrawal of friendly forces. In these applications, the mini-HDD bores are loaded with slurry explosives that can be detonated when desired. This idea may be adaptable to civilian applications, such as removal of spillway plugs during floods, removal of unstable slope materials, demolition of building foundations, and other applications.

In the decade since mini-HDD was developed, it has become an established, preferred method for installation of small-diameter water, gas, and cable lines in congested urban areas and environmentally sensitive areas. Continued applications-oriented R&D could markedly broaden its use and help solve particularly challenging problems.

5.4 Recommendations for Microtunneling

To increase the number of successfully completed microtunneling projects, there needs to be increased funding for proper site investigation. More extensive site investigations should help reduce uncertainties, enlighten the contractor for appropriate machine preparation, and limit changed conditions claims. This funding should be used to increase the number of borings on a project, particularly where varying site conditions exist, and the number of tests that are performed on the soil/rock samples.

Engineers, owners, and contractors need to learn more about the applicability of microtunneling techniques so that microtunneling can be specified correctly and at appropriate locations. The education should include shared (honest) information about completed projects, both successful and unsuccessful, to establish applicability and limitations of the technique. Special attention should be given to challenging projects where special provisions or techniques were required.

There needs to be an increase, industry-wide, in the understanding of driving techniques and theories, proper machine selection and required modifications, and machine setup. Many of the documented pipe failures, settlement, heave, and steering problems are a direct result of operator error, improper machine selection, or incorrect machinery setup. Currently most operators learn by the "trial by fire" method, and they must experience problems in the field to learn from the mistakes. Proper driving techniques for various ground conditions need to be established and taught to machine operators.

Results of various soil tests and the effect of these results on microtunneling operations need to be thoroughly understood by engineers and contractors. This should include an understanding of how the machines should be modified to handle different types of soil conditions. Specific guidelines for appropriate machine modifications need to be established.

Further research and development efforts need to be concentrated on rock cutters and other methods of excavating hard ground or rock conditions. This should include designs for mixed-bit configurations on the cutterhead to handle a mixture of soil types on a single drive as well as mixed face conditions. Field tests need to be performed on these head configurations to establish a database from which further design improvements can be made.

There needs to be additional research on the beneficial effects of lubrication and the proper selection of slurry mixtures. This research needs to evaluate lubrication mixtures in different soil types and establish recommendations for slurry stabilization in unstable ground conditions. A measuring device capable of measuring slurry density and viscosity also needs to be incorporated into the slurry system. This device could be placed in the inlet and outlet slurry lines to monitor excavated solids. The information obtained from such a device would help to prevent overexcavation in unstable ground conditions.

With current technology, microtunneling is not possible around a curved alignment. Additional research needs to be performed to develop control systems, not dependent on a straight laser beam projection, to enable the machine to steer around curves. In addition, pipe joints capable of handling eccentric loads associated with curves and able to remain watertight also need to be developed.

Owners, engineers, and contractors need to realize that all underground construction is risky. However, the perception of risk is changing, industry-wide, as the involved parties begin to understand the need for sharing risk on a project. When all parties share risk, the severity of claims and litigation will be greatly reduced, contributing to successful projects.

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Appendix A
Glossary

Adapter Ring. In microtunneling, a fabricated ring, usually made from steel, that serves to mate the microtunneling machine to the first pipe section. This ring is intended to create a waterproof seal between the machine and the spigot of the first joint.

Auger. A flighted drive tube having hex couplings at each end, to transmit torque to the cutting head and transfer spoil back to the machine.

Auger Boring. A technique for forming a bore from a drive pit to a reception pit by means of a rotating cutter head. Spoil is removed back to the drive shaft by helically wound auger flights rotating in a steel casing. The equipment may have limited steering capability but does not provide continuous support to the excavation face, a key distinction from microtunneling. See Guided Auger Boring.

Auger Machine. A machine used to drill earth horizontally by means of a cutting head and auger or other functionally similar device. The machine may be either cradle or track type.

Auger MTBM. A type of Microtunnel boring machine in which the excavated soil is removed to the drive shaft by auger flights passing through the product pipeline pushed in behind the MTBM.

Automated Spoil Transportation System. The automated spoil transportation system conveys the excavated spoil from the tunnel face to the drive or jacking shaft.

Back Reamer. A cutting head attached to the leading end of a drill string to enlarge the pilot bore diameter during a pull-back operation to enable the product pipe to be installed.

Backstop/Thrustblock. Reinforced area of the entrance pit wall directly behind the track or jacking frame.

Band. A ring of steel welded at or near the front of the lead section of casing to cut relief and strengthen the casing. This band also provides annular space between the machine and the soil, into which bentonite or other lubricants can be injected.

Bent Sub. An offset section of drill stem close behind the drill head that allows steering corrections to be made by rotation of the drill string to orientate the cutting head. Frequently used in directional drilling in rock.

Bits. Replaceable cutting tools on the cutting head or drill string.

Can. A principal module which is part of a shield machine as in microtunneling or TBM's. Two or more may be used, depending on the installation dimensions required and the presence of an articulated joint to facilitate steering. May also be referred to as a trailing tube.

Carrier Pipe. The tube which carries the product being transported and which may go through casings at highway and railroad crossings. It may be made of steel, concrete, clay, plastic, ductile iron, or other materials.

Cased Bore. A bore in which a pipe, usually a steel sleeve, is inserted simultaneously with the boring operation. Often associated with auger boring.

Casing. A pipe to support a bore. Usually not a product pipe.

Casing Adapter. A circular mechanism to provide axial and lateral support to a casing that is smaller in diameter than the casing pusher.

Casing Pipe. A pipe installed as external protection to a Product Pipe.

Chemical Stabilization. Renovation work which involves the introduction of one or more compounds in solution through pipes and into surrounding ground, producing a chemical reaction. Such stabilization may perform a variety of functions such as the sealing of cracks and cavities, the provision of a new wall surface with improved hydraulic characteristics, or soil stabilization.

Closed Face. The ability of a tunnel boring machine to provide support to the excavation face by closing or sealing the facial opening of the machine to prevent or slow the entrance of soils into the machine. Also may be the bulkheading of a hand dug tunnel to slow or stop the inflow of material.

Close-Fit. Description of a lining system in which the new pipe makes close contact with the defective pipe at normal or minimum diameter. An annulus may occur in sections where the diameter of the defective pipe is in excess of this.

Collaring. The initial entry of casing or a cutting head into the earth.

Compression Rings. In microtunneling, a ring, typically made of 1/4- to 1/2-in. plywood, that is fitted between the end bearing area of the bell and spigot to help distribute applied loads more uniformly. The compression ring is attached to the trailing end of each pipe and is compressed between the pipe sections during jacking. The compression rings compensate for slight misalignment, pipe ends that are not perfectly square, gradual steering corrections, and other pipe irregularities. Compression rings are also referred to as Spacers.

Control Console. An electronic unit, located on the ground surface, that houses the controls for a microtunneling machine. The machine operator will drive the tunnel from the control console. Electronic information will be transmitted to the control console from the heading of the machine. This information includes head position, steering angle, jacking force, progression rates, machine face torque, slurry and feed line pressures, and laser position. Some control consoles are equipped with a computer that tracks the data for a real-time analysis of the tunnel drive.

Control Panel. In mini-horizontal directional drilling, the panel containing all of the gauges, hydraulic valves, control levers, and water pumps to operate the entire drill rack.

Cover or Overburden. The depth of material from the top of the ground (top of pavement, top of ties, etc.), to the top of the casing or tunnel measured vertically.

Crossing. Trenchless installation in which the primary purpose is to provide one or more passages beneath a surface obstruction.

Cured-in-Place Pipe (CIPP). A system in which a thin flexible tube of polymer or glass fiber fabric is impregnated with resin and forced into position on the inner wall of a defective pipeline before curing the resin to harden the material. The uncured liner may be installed by winch or inverted by water or air pressure, with or without the aid of a turning out winch.

Cutterhead/Cutting Head. Any tool or system of tools on a common support which excavates at the face of a bore. Usually applies to mechanical methods of excavation.

Directional Drilling. A steerable system for the installation of pipes, conduits, and cables in a shallow arc using a surface-launched drilling rig. Traditionally the term applies to large-scale crossings in which a fluid-filled pilot bore is drilled without rotating the drill string, and this is then enlarged by a washover pipe and back reamer to the size required for the product pipe. The required deviation during pilot boring is provided by the positioning of a bent sub. Tracking of the drill string is achieved by the use of a downhole survey tool.

DRB. Dispute Review Board.

Drill Bit. A tool which cuts the ground at the head of a drill string, usually by mechanical means.

Drill String. (1) The total length of drill rods/pipe, bit, swivel joint, etc., in a drill borehole; (2) system of rods used with cutting bit or compaction bit attached to the drive chuck.

Drilling Fluid/Mud. A mixture of water and usually bentonite or polymer continuously pumped to the cutting head to facilitate the removal of cuttings and to stabilize the boreholes. In directional drilling, the fluid also cools the head and lubricates the installation of the product pipe. In suitable ground conditions, water alone may be used.

Drive/Entry/Jacking Shaft/Pit. Excavation from which trenchless technology equipment is launched for the installation or renovation of a pipeline, conduit, or cable. May incorporate a thrust wall to spread reaction loads to the ground.

Dry Bore. Any drilling system not employing drilling fluid in the process. Usually associated with guided impact moling, but also some rotary methods.

Earth Piercing. The use of a tool which comprises a percussive hammer within a suitable casing, generally of torpedo shape. The hammer may be pneumatic or hydraulic. The term is usually associated with nonsteered devices without rigid attachments to the launch pit, relying upon the resistance (friction) of the ground for forward movement. During operation, the soil is displaced, not removed. An unsupported bore may be formed in suitable ground or a pipe drawn in, or pushed in, behind the impact moling tool. Cables may also be drawn in. The term is commonly used in North America.

Earth Pressure Balance (EPB) Machine. Type of microtunneling or tunneling machine in which mechanical pressure is applied to the material at the face and controlled to provide the correct counter-balance to earth pressures in order to prevent heave or subsidence. The term is usually not applied to those machines where the pressure originates from the main pipe jacking rig in the drive shaft/pit or to systems in which the primary counter-balance of earth pressures is supplied by pressurized drilling fluid slurry.

Entry/Exit Angle. In a horizontal directional drilling/guided boring system, the angle to the ground surface at which the drill string enters and exits in forming the pilot bore. This can also be used in microtunneling to describe the angle between the machine and the horizontal at launch.

EPB. Abbreviation for earth pressure balance.

Expander. A tool which enlarges a bore during a pull-back operation by compression of the surrounding ground rather than by excavation, sometimes used during a thrusting process as well as during pull-back.

Feedline. A series of hoses or pipes that transport water/slurry from the ground surface to the face of a microtunneling machine. Feedline pressure, in conjunction with slurry line pressure, is used to maintain soil stabilization at the face of a slurry microtunneling machine.

Flight. The spiral plates surrounding the tube of an auger.

Fluid Assisted Boring/Drilling. A type of guided boring technique using a combination of mechanical drilling and pressurized fluid jets to provide the soil cutting action.

Fold-and-Form Pipe (FFP). A lining system in which an extended thermoplastic is folded, installed in its folded form by winching, and rounded inside the sewer.

Free Boring. Auger boring without a casing.

GDSR. Geotechnical Design Summary Report.

Grade. The elevations shown on plans and/or survey stakes for the installation of the carrier pipe. It is occasionally used to give elevations for casing. In most cases, it is given to the flow line but can also be given to the top of the pipe or casing.

Ground Mat. Metal mats rolled out on either side of drill rack for operators and crew to stand on during operation to give grounding protection in case of electrical strike.

Ground Mat Cables. Cables connecting the drill rack to the ground mats.

Ground Rod. This is a copper/brass rod which is hand driven into the ground and is connected to the drill rack and mats to provide adequate grounding of unit and personnel.

Ground Rod Cable. Cable connecting the mats and drill rig to the ground rod.

Grout. A material such as a cement slurry, sand, or pea gravel that is pumped into voids.

Grouting. Filling of the annular space between the carrier pipe and the new product pipe. Grouting is also used to fill the space around laterals and between the new pipe and manholes. Other uses of grouting are for localized repairs of defective pipes and ground improvement prior to excavation during new installations.

Guided Auger Boring. A term applied to auger boring systems which are similar to microtunneling, but with the guidance mechanism actuator sited in the drive shaft (e.g., a hydraulic wrench which turns a steel casing with an asymmetric face at the cutting head). The term may also be applied to those auger boring systems with rudimentary articulation of the casing near the head activated by rods from the drive pit.

Guided Boring. A steerable system for the installation of pipes, conduits, and cables using a pit-launched drilling rig. A pilot bore is drilled using a rotating drill string and is then enlarged by a back reamer to the size required for the product pipe. The necessary deviation during pilot boring is provided by a slanted face to the drill head, an asymmetric drill head, eccentric fluid jets, or a combination of these usually in conjunction with a locator.

Horizontal Earth Boring. (Auger Boring, Boring, and Jacking.) The installation of a casing where the spoil is removed by the use of augers.

Horizontal Earth Boring Machine. A machine used to bore horizontally through the earth by means of a rotating tool, or nonrotating pushing or piercing tool.

Horizontal Directional Drilling. See Directional Drilling.

Horizontal Rotary Drilling. (Wet Boring, Mud Jacking, Bentonite Boring, Slurry Boring, and Rotary Boring). The mechanical installation of pipe or casing by rotating methods which do not use augers for the removal of spoil. Usually uses a fluid of water and bentonite to remove spoil.

Host Pipe. The tube which carries the product being transported and which may go through casings at highway and railroad crossings. It may be made of steel, concrete, clay, plastic, ductile iron, or other materials. On occasion it may be bored directly under the highways and railroads.

Impact Machines. A type of machine that pierces the earth (piercing tool) or rams an object to produce a bore (ramming machine).

Impact Moling. The use of a tool which comprises a percussive hammer within a suitable casing, generally of torpedo shape. The hammer may be pneumatic or hydraulic. The term is usually associated with nonsteered or limited steering devices without rigid attachments to the launch pit, relying upon the resistance (friction) of the ground for forward movement. During operation, the soil is displaced, not removed. An unsupported bore may be formed in suitable ground, or a pipe drawn in, or pushed in, behind the impact moling tool. Cables may also be drawn in.

Impact Ramming. See pipe ramming.

In Line/On Line Replacement. The breaking out of an existing pipeline and the installation of a new service on the same line.

Infiltration/Inflow (I/I). The total quantity of water from both infiltration and inflow without distinguishing the source.

Interjack Pipes. Pipes specially designed for use with an intermediate jacking station.

Intermediate Jacking Station (IJS). A fabricated steel cylinder fitted with hydraulic jacks that is incorporated into a pipeline between two interjack pipes. Its function is to distribute the jacking load over the pipe string on long drives.

Internal Inspection. Means of ascertaining the condition of pipelines whether by personnel entry, visual inspection, or the use of remote-control instrumentation.

Invert. The elevation at the bottom of the casing.

Jacking. The actual pushing of pipe or casing in an excavated hole. This is usually done with hydraulic cylinders (jacks), but has been done with mechanical jacks, air jacks, and other devices.

Jacking Frame. A structural component that houses the hydraulic cylinders used to propel the microtunneling machine and pipeline. The jacking frame serves to distribute the thrust load to the pipeline and the reaction load to the shaft wall or thrust wall. Jacking units are specifically designed for the microtunneling process, offering compactness of design and high thrust capacity.

Jacking Pipes. Pipes designed to be installed using pipe jacking or microtunneling techniques.

Jacking Shield. A fabricated steel cylinder from within which the excavation is carried out either by hand or machine. Incorporated within the shield are facilities to allow it to be adjusted to control line and grade.

Jet Cutting. A type of guided boring technique using pressurized fluid jets to provide the soil cutting action.

Launch Pit. As for drive pit but more usually associated with "launching" a trenchless technology excavation tool.

Launch Seal. In microtunneling, a mechanical seal, usually composed of a rubber flange that is mounted to the wall of the drive shaft. The flange seal is distended by the MTBM as it passes through creating a seal to prevent water/lubrication inflow into the shaft during tunneling operations..

Lead Pipe. The leading pipe manufactured to fit the rear of a jacking shield and over which the trailing end of the shield is fitted.

Line. (1) The specified direction of the proposed bore in a horizontal plane; (2) (path) the distance between two points as laid out by a survey crew for the installation of pipelines and their bores and tunnels.

Lining. An internal, nonstructural coating or lining material applied to a pipe.

Live Insertion. Installation of a liner while the product pipe remains in service. Also referred to as on-line renovation.

Localized Repair. Repair work on a pipe, particularly sewerage, to an extent less than the run between two access points.

Locator. An electronic instrument used to determine the position and strength of electro-magnetic signals emitted from a transmitter sonde in the pilot head of a boring system, in an impact moling tool, or from existing services which have been energized. Sometimes referred to as a walkover system.

Marsh Funnel. An instrument used to determine viscosity. For trenchless applications, used to determine slurry viscosity. The most commonly used device for determining viscosity in the construction industry. The marsh funnel test is performed by pouring a slurry sample through a screen at the top of the funnel to trap large particulates. After the funnel is filled, the bottom of the funnel is opened, and the slurry is allowed to flow. The flow rate is calculated as the number of seconds required for a quart of slurry to drain out of the funnel.

Measurement While Drilling (MWD). Borehole survey instrumentation that provides continuous information simultaneously with drilling operations, usually transmitting to a display at or near the drilling rig.

Medi-Rig. Steerable surface-launched drilling equipment for the installation of pipes, conduits, and cables. Applied to intermediate sized drilling rigs used as either a small directional drilling machine or a large guided boring machine. Tracking of the drill string may be achieved by either a downhole survey tool or a locator.

Microtunneling. A remotely controlled, guided, pipe-jacking process that provides continuous support to the excavation face. The guidance system usually consists of a laser mounted in the jacking pit as a reference with a target mounted inside the microtunneling machine's articulated steering head. The microtunneling process does not require personnel entry into the tunnel. A key element of microtunneling is the ability to control the stability of the face by applying mechanical or fluid pressure to the face to balance the groundwater pressure.

Mini-Horizontal Directional Drilling (Mini-HDD). Surface-launched method for installing product pipes or utility lines of diameters up to 10 inches, in lengths up to 600 feet or more, at depths typically less than 15 feet. Maximum thrust/pullback capability is approximately 20,000 pounds.

Mixed Face. A soil condition that presents two or more different types of material in the cross-section of the bore.

Mole. See impact moling.

Mole Ploughing. Burying a pipeline by pulling a plough through the ground while a continuous length of pipe is fed into the top of the plough and laid out underground from the tail of the plough. An alternate ploughing technique may use a plough blade with a bullet at the end to create a tunnel beneath the surface into which a pipe may be pulled.

Muck. As a noun, it means the same as spoil. As a verb, it means to dig as in "muck out the hole."

Open Cut. Excavation to the required underground level for the installation, maintenance or inspection of a pipe, conduit or cable. The excavation is then backfilled and the surface restored.

Ovality. The difference between the maximum diameter divided by the mean diameter at any one cross section of a pipe, generally expressed as a percentage.

Personnel Entry. Describes any trenchless technology process which requires an operative to enter a pipe, duct, or bore. The minimum size for which this is permissible is generally defined by national health and safety legislation.

Piercing Tool. An impact type of compacting device for boring.

Piling. Rigid supports, driven vertically to provide wall support.

Pilot Bore. The action of creating the first (usually steerable) pass of any boring process which later requires back reaming or similar enlarging. Most commonly applied to guided boring, directional drilling, and 2-pass microtunneling systems.

Pipe Bursting. A technique for breaking the existing pipe by brittle fracture, using force from within, applied mechanically, the remains being forced into the surrounding ground. At the same time a new pipe, of the same or larger diameter, is drawn in behind the bursting tool. The pipe bursting device may be based on a pneumatic impact moling tool to exert diverted forward thrust to the radial bursting effect required, or by a hydraulic device inserted into the pipe and expanded to exert direct radial force.

Pipe Displacement. See Pipe Bursting.

Pipe Eating. A technique, usually based on microtunneling, in which a defective pipe is excavated together with the surrounding ground as for a new installation. The microtunneling shield machine will usually need some crushing capability to perform effectively. The defective pipe may be filled with grout to improve steering performance. Alternatively, some systems employ a proboscis device to seal the pipe in front of the shield.

Pipe Jacking. A system of directly installing pipes behind a shield machine by hydraulic jacking from a drive shaft such that the pipes form a continuous string in the ground.

Pipe Pusher. A machine that pushes or pulls a rod or pipe to produce a bore by means of compaction without rotation or impact.

Pipe Ramming. A nonsteerable system of forming a bore by driving an open-ended steel casing using a percussive hammer from a drive pit. The soil may be removed from the casing by auguring, jet-cutting, or compressed air. In appropriate ground conditions, a closed pipe may be used.

Pipe Splitting. Technique for breaking an existing pipe by longitudinal splitting. At the same time, a new pipe of the same or larger diameter is drawn in behind the splitting tool.

Point Source Repair. See localized repair.

Preparatory Cleaning. Internal cleaning of pipelines, particularly sewers, prior to inspection or construction, usually with water jetting.

Product Pipe. Permanent pipeline for operational use.

Pull-Back. That part of a guided boring, mini-horizontal directional drilling (HDD), or mini-HDD process in which the drill string is pulled back through the bore to the entry pit, usually installing a product pipe at the same time.

Pull-Back Force. The tensile load applied to a drill string during the pullback process. Guided boring and directional drilling rigs are generally rated by their maximum pullback force.

Reception/Exit Shaft/Pit. Excavation into which trenchless technology equipment is driven and recovered following the installation or renovation of the product pipe, conduit, or cable.

Rehabilitation. In situ renovation to improve the performance and extend the life of a defective pipeline, incorporating the fabric of that pipeline. Rehabilitation may be to address structural and/or hydraulic weakness.

Reinstatement/Restoration. The backfilling, compaction, and resurfacing of any excavation in order to restore the surface and underlying structure to enable it to perform its original function.

Remote Control System. The system that monitors and controls the MTBM, the automated transport system, and the guidance system, from a location not in the MTBM.

Rerounding. A preparatory process which involves the insertion of an expansion device into a distorted pipe to return it to a circular cross section. This is usually carried out prior to the insertion of a permanent liner or support band.

Resin Injection. The localized repair of pipes, usually sewers, by injection of a resin formulation into cracks or cavities which subsequently cures to prevent leakage and further deterioration. It may also increase the structural strength of the pipeline.

Retrieval Seal. A mechanical seal usually comprised of a rubber flange that is distended by the MTBM. In microtunneling, similar to the launch seal but used during the holing-out operation. Serves to keep water from infiltrating into the reception shaft.

Robot. A remote-control device with closed circuit television (CCTV) monitoring, used mainly for localized repair work such as cutting away obstructions, reopening lateral connections, and injecting resin into cracks and cavities.

Roller Cone Bit or Reamer. A bit or reamer in which the teeth rotate on separate, internal shafts that are usually aligned perpendicular to line; used for boring rock.

Rotary Rod Machine. A machine used to drill earth horizontally by means of a cutting head attached to a rotating rod (not an auger). Such drilling may include fluid injected to the cutting head through a hollow rod.

Sheet Piling. See Piling.

Shield. A steel cylinder at the face of a tunnel or casing that provides hazard protection, which may include a mechanical excavator and may be steerable.

Shoring. See Piling.

Skin Friction. Resistance to thrust caused by the product of normal stress or soil pressure and friction or adhesion around the casing.

Sleeve Pipe. A pipe installed as external protection to a Product Pipe.

Sliplining. Insertion of a new pipe by pulling or pushing it into the existing pipe and grouting the annular space. The pipe used may be continuous or a string of discrete pipes. The latter is also referred to as segmental sliplining.

Slurry Chamber. Located behind the cutting head of a slurry microtunneling machine. Excavated material is mixed with drilling fluid in the chamber for slurry transport to the surface.

Slurry Line. A series of hoses or pipes that transport tunnel muck and slurry from the face of a slurry microtunneling machine to the ground surface for separation. The slurry line pressure, in conjunction with the feedline pressure, is used for soil stabilization at the face of a slurry microtunneling machine.

Slurry Separation Plant. A series of tanks where excavated material is separated from tunnel slurry. A hydro-cyclone, shaker screen, or sand hopper can be incorporated into a slurry separation plant to increase soil removal.

Sonde Housing. Integral unit in the direction drill head which also houses the sonde radio sending unit.

Spacers. See Compression Rings.

Spiral Lining. A technique in which a ribbed plastic strip is spirally wound by a winding machine to form a liner which is inserted into a defective pipeline. The annular space may be grouted or the spiral liner expanded to reduce the annulus and form a close-fit liner. In larger diameters, the finished liner may be formed on the surface and installed by conventional sliplining methods.

Spiral Weld Pipe (Casing). Pipe made from coils of steel plate by wrapping around a mandrel in such a manner that the welds are a spiral helix.

Split Design. A boring machine having the capability of being broken down into two or more elements to reduce the lifting weight.

Spoil (Muck). Earth, rock and other materials displaced by a tunnel or casing and removed as the tunnel or casing is installed. In some cases, it is used to mean only the material that has no further use.

Spray Lining. A technique for applying a lining of cement mortar or resin by rotating a spray head which is winched through the existing pipeline.

SSES. Sewer System Evaluation Survey of tributary sewer systems with levels of infiltration and inflow (I/I).

Stakedown Plate. A plate staked to the ground to stabilize the forward end of the drill rack.

Subsaver. A replaceable sub on the carriage motor to which the drill pipe is connected.

Sump. A depression in the pit to allow for the collection of water and the installation of a pump for water removal.

Survey Tools. Downhole equipment and instruments used to determine the position of a bore in directional drilling or site investigation.

Swab (Bull Plug). A steel plug which is pulled through a horizontal bore to remove the cuttings.

Swageing. The reduction in diameter of a polyethylene pipe by passing it through one or more dies. The die may be heated if necessary.

Swivel Pulling. Used to attach service (to be pulled into drilled hole) to drill pipe.

Target Shaft/Pit. See Reception/Exit Shaft/Pit.

Teeth. See Bits.

Thrust Bearing. A bearing used to isolate the thrust and torque of the machine from the pipeline.

Thrust Boring. A method of forming a pilot bore by driving a closed pipe or head from a thrust pit into the soil which is displaced. Some small-diameter models have steering capability achieved by a slanted pilot-head face and electronic monitoring, generally in conjunction with a locator. Back reaming may be used to enlarge the pilot bore.

Thrust Gauge. In mini-horizontal directional drilling, a gauge showing the hydraulic pressure during the thrusting of the carriage and drill string.

Thrust Ring. A fabricated ring that is mounted on the face of the jacking frame. It is intended to transfer the jacking load from the jacking frame to the thrust bearing area of the pipe section being jacked. This term is usually associated with microtunneling operations.

Torque. The rotary force available or applied at the drive chuck.

Track. A set of longitudinal rails mounted on cross members that support and guide a boring machine.

Trenching. See Open Cut.

Trenchless Technology. Refers to a family of methods, materials, and equipment that can be used for installation of new or replacement or rehabilitation of existing underground infrastructure with minimal disruption to surface traffic, business, and other activities, as opposed to open trenching and its associated major disruptions to surface activities.

Uncased Bore. Any bore without a lining or pipe inserted, i.e. self-supporting, whether temporary or permanent.

Underground Utility. Active or inactive services or utilities below ground level.

Upsizing. Any method which increases the cross-sectional area of an existing pipeline by replacing with a larger diameter pipe.

Walkover System. See locator.

Washover Pipe. A rotating drill pipe of larger diameter than the pilot drill pipe and placed around it with its leading edge less advanced. Its purpose is to provide stiffness to the drilling pipe in order to maintain steering control over long bores, to reduce friction between the drill string and the soil, and to facilitate mud circulation. See directional drilling.

Water Jetting. Internal cleansing of pipelines using jets of water at high pressure.

Water Table. The elevation of the ground water.

Wetout. The process of injecting resin into and distributing it throughout a hose or tube which will then be installed into the pipeline and cured in place.

Wing Cutters. Appendages on auger boring machine cutting heads that will open to increase the cutting diameter of the head when turned in a forward direction, and close when turned in a reverse direction. They are used to cut clearance for the casing pipe.

Wrapped Casing (Wrapped Pipe). A coating on pipe for protection from corrosion, usually composed of asphalt and asphalt coated paper. Some coatings may contain plastic, fiberglass, coal tar, or other materials.

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These guidelines mark the completion of the Construction Productivity Advancement Research (CPAR) project "Trenchless Construction: Evaluation of Methods and Materials to Install and Rehabilitate Underground Utilities." CPAR is a cost-shared U.S. Army Corps of Engineers and construction industry research program. This 3-year project was conducted by the U.S. Army Engineer Waterways Experiment Station and the Trenchless Technology Center at Louisiana Tech University.

The overall objective of this study was to develop guidelines that owners, engineers, and contractors could use to evaluate and select appropriate trenchless methods and equipment for their project requirements and site conditions.

The guidelines focus on the three major elements of trenchless technology investigated in this study: rehabilitation of existing pipelines using cured-in-place (CIPP) and fold-and-formed pipe (FFP) methods, installation of small-diameter (2- to 10-in.) pipe lines using mini-horizontal directional drilling (mini-HDD) and installation of larger diameter pipelines using microtunneling. The guidelines are based primarily on the results of extensive laboratory and field investigations.

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